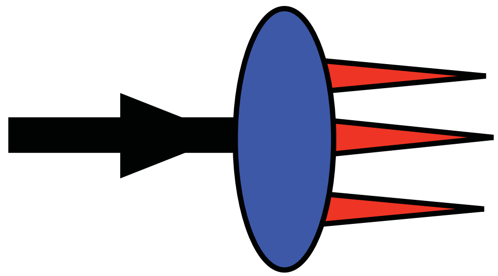
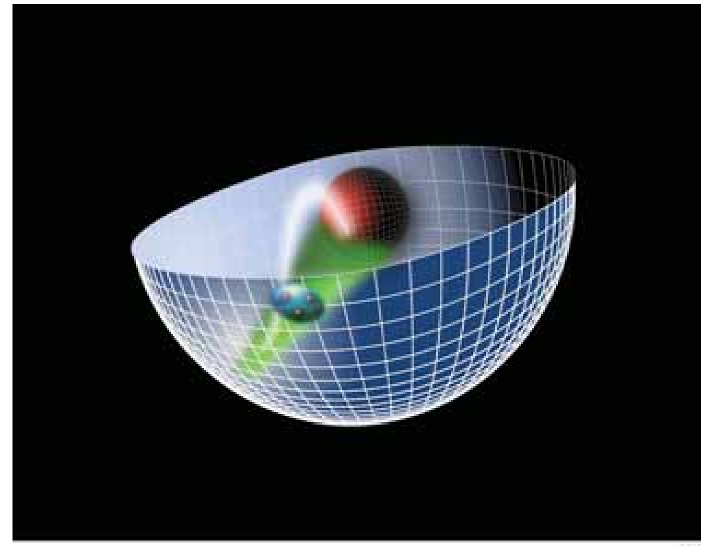
QCD at the Light-Front



$$\Psi_n(x_i, \vec{k}_{\perp i}, \lambda_i)$$



LC 2010

University of Valencia

June 17, 2010

Stan Brodsky SLAC NATIONAL ACCELERATOR LABORATORY & *CP3 -Origins*

Light Cone 2010

Relativistic Hadronic and Particle Physics

Valencia, Spain
June, 14-18, 2010

Local Organizing Committee

Chairpersons

- Joannis Papavassiliou (Universidad de Valencia-IFIC, Spain)
- Vicente Vento (Universidad de Valencia-IFIC, Spain)

Scientific Secretaries

- Arlene Cristina Aguilar (Universidade Federal ABC, Brazil)
- Aurore Courtoy (INFN Sezione di Pavia, Italy)
- Jorge Portolés (IFIC, Spain)

I•L•C•A•C, Inc.

The International Light Cone Advisory Committee, Inc.

Previous Meetings:

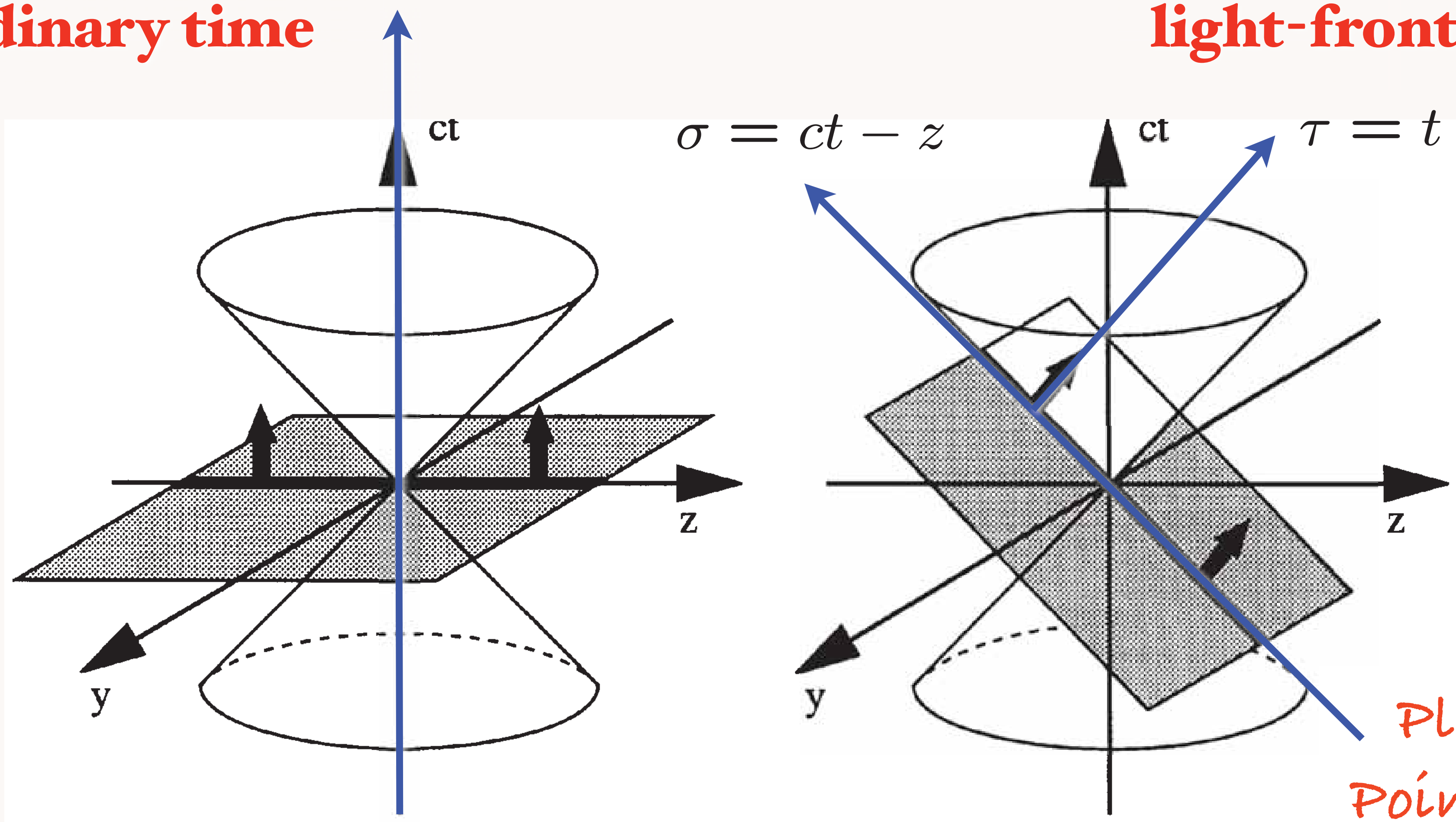
Place	Organizer	Number of Participants
Light Cone 2009	Frederico, Bakker (Pictures)	
Light Cone 2008	Mathiot, Bakker & Diehl: Mulhouse Pictures 1, 2	58
Amsterdam 2004	Bakker, Boer & Mulders	49
Durham 2003	Stirling, Dalley & Wilkinson	54
Los Alamos 2002	Johnson, Kisslinger, Burkardt & Pate	about 50
Trento2001	Bassetto, Griguolo, Nardelli & Vian	77
Heidelberg2000	Pauli, Werner & Hollenberg	57
Adelaide99	Hollenberg, McKellar & Williams	55
StPetersburg98	Lipatov	70
LesHouches97	Grange	about 80
Ames96	Vary	75
Regensburg95	Werner	about 70
Seattle94	Miller	about 80
Zürich93	Wyler	about 60
Dallas92	McCartor	about 70
Heidelberg91	Pauli	about 50

P.A.M Dirac, Rev. Mod. Phys. 21, 392 (1949)

Dirac's Amazing Idea: The Front Form

Evolve in ordinary time

Evolve in light-front time!



Plessas: Point Form

Instant Form | **Front Form**

Each element of flash photograph illuminated at same Light Front time

$$\tau = t + z/c$$

Evolve in LF time

$$P^- = i\frac{d}{d\tau}$$

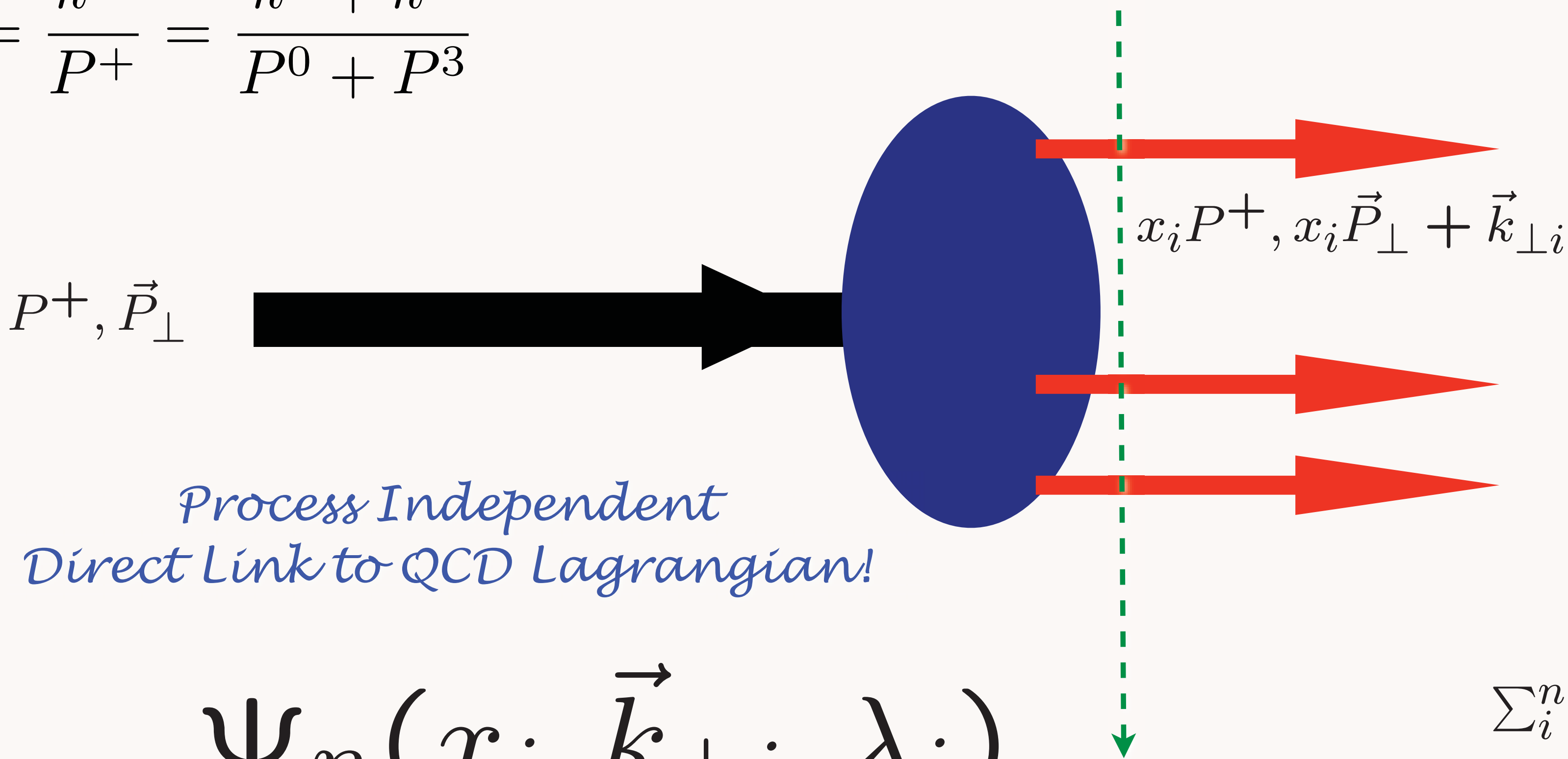
Causal, Trivial Vacuum

Laser Physics is Light-Front Physics

Light-Front Wavefunctions: rigorous representation of composite systems in quantum field theory

$$x = \frac{k^+}{P^+} = \frac{k^0 + k^3}{P^0 + P^3}$$

Fixed $\tau = t + z/c$



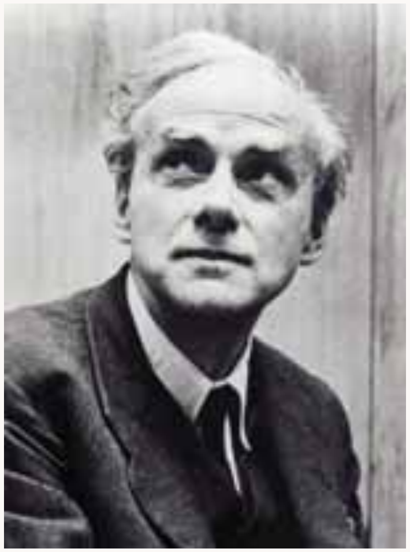
Process Independent
Direct Link to QCD Lagrangian!

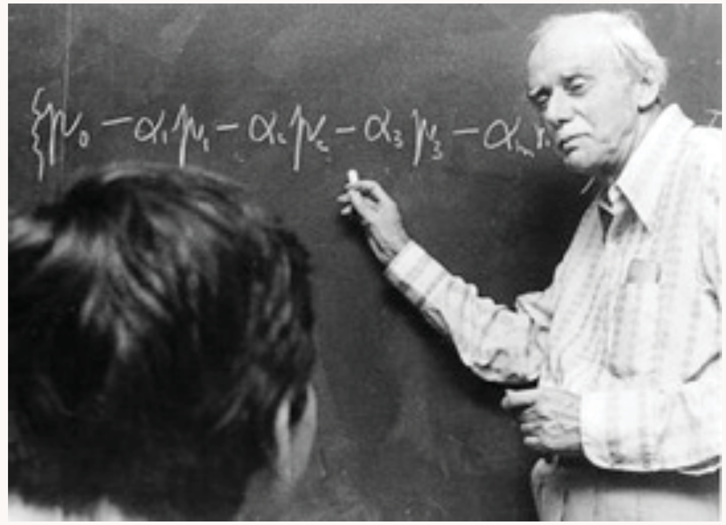
$$\Psi_n(x_i, \vec{k}_{\perp i}, \lambda_i)$$

$\sum_i^n x_i = 1$

$\sum_i^n \vec{k}_{\perp i} = \vec{0}_\perp$

Invariant under boosts! Independent of P^μ





"Working with a front is a process that is unfamiliar to physicists.

But still I feel that the mathematical simplification that it introduces is all-important.

I consider the method to be promising and have recently been making an extensive study of it.

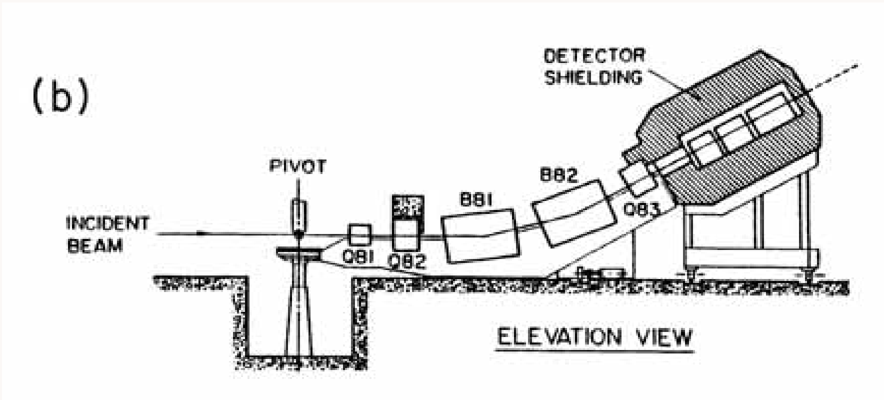
It offers new opportunities, while the familiar instant form seems to be played out." - P.A.M. Dirac (1977)

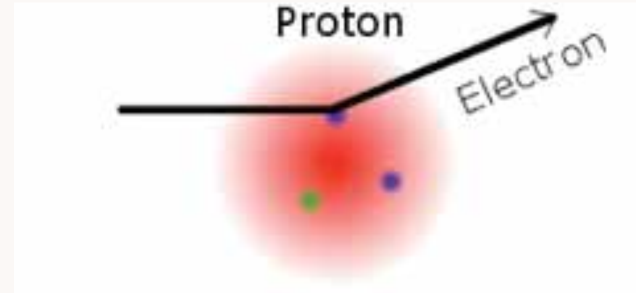
1967 SLAC Experiment:

Scatter 20 GeV/c Electrons on protons in a Hydrogen Target

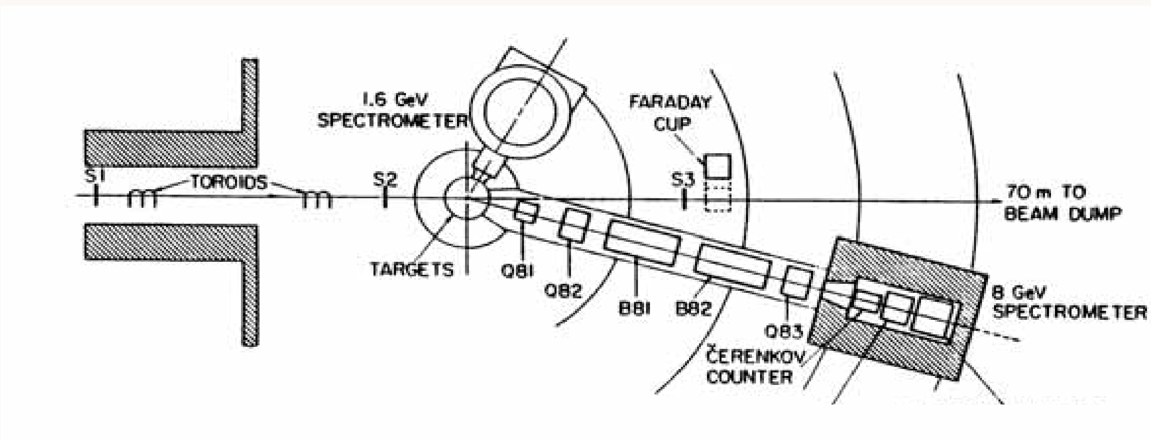
Discovery of the Quark Structure of Matter

$$ep \rightarrow e'X$$

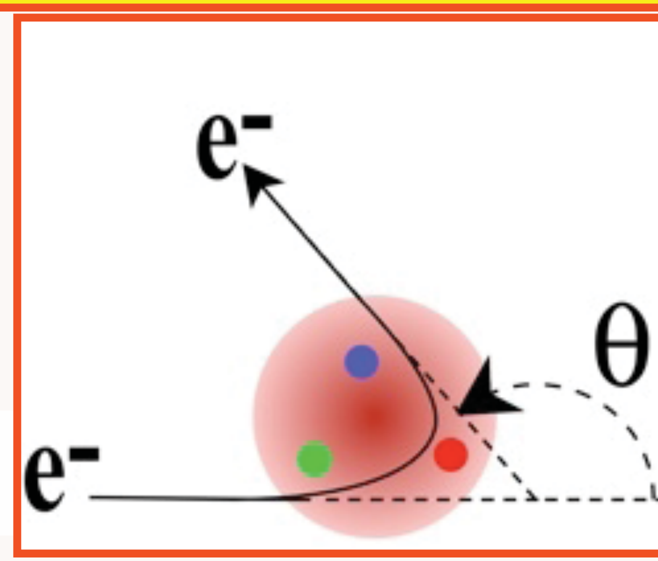




Discovery of quarks!

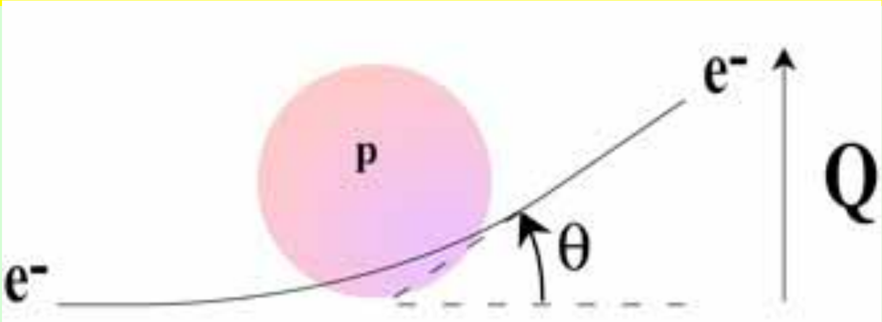


Deep inelastic scattering: Experiments on the proton and the observation of scaling

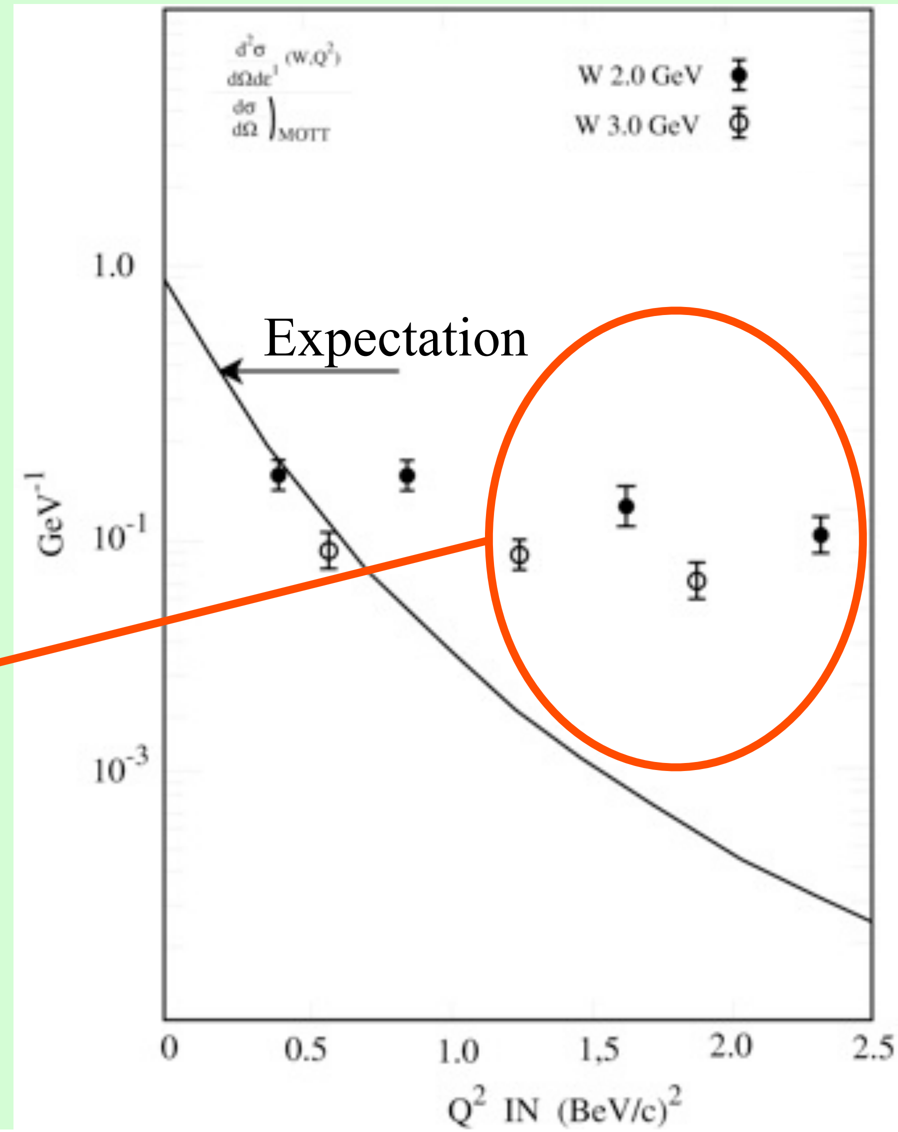


Friedman, Kendall, Taylor: Nobel Prize

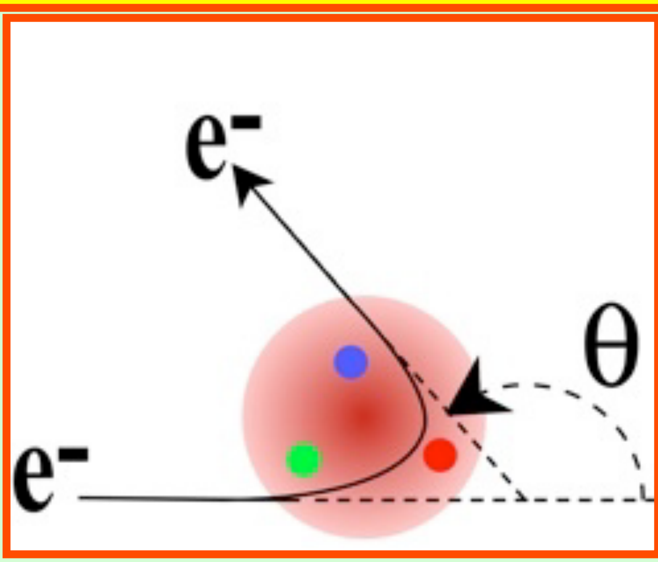
Deep inelastic electron-proton scattering



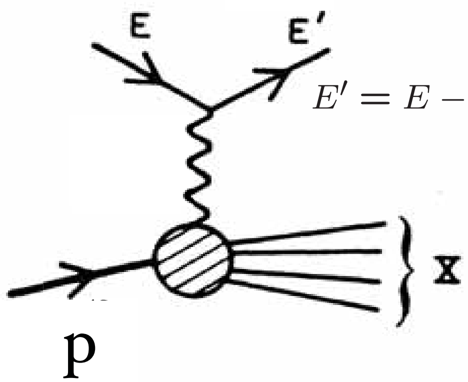
- Rutherford scattering using *very* high-energy electrons striking protons



Discovery of quarks!



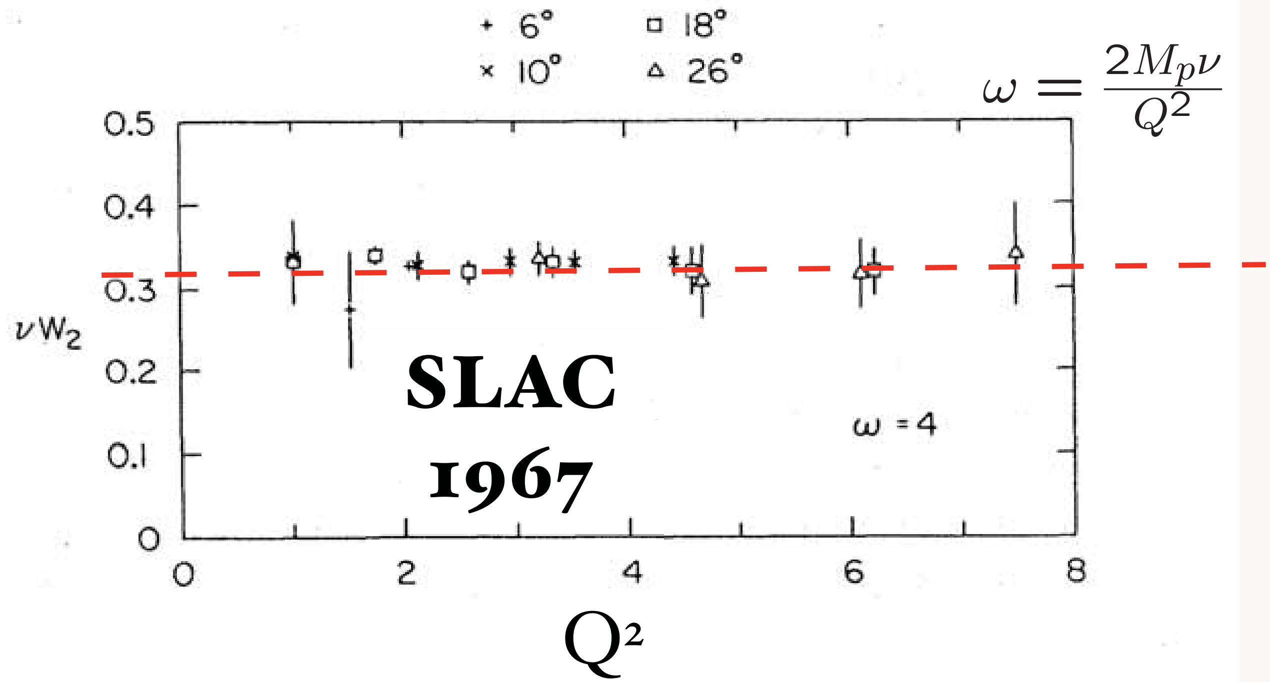
$$ep \to e'X$$



$E' = E - \nu, \vec{q}$

$$Q^2 = \vec{q}^2 - \nu^2$$

$$\omega = \frac{2M_p\nu}{Q^2}$$



No intrinsic length scale !

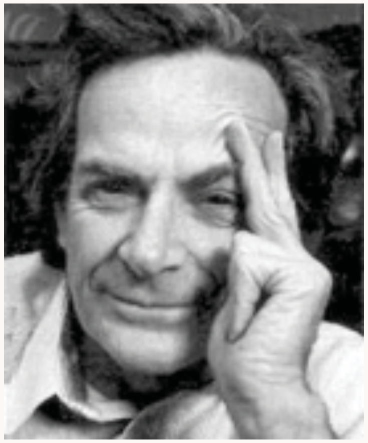
Measure rate as a function of energy loss ν and momentum transfer Q

$$x_{bj} = \frac{1}{\omega_{bj}} = \frac{Q^2}{2q \cdot p}$$

Discovery of Bjorken Scaling

Electron scatters on point-like quarks!

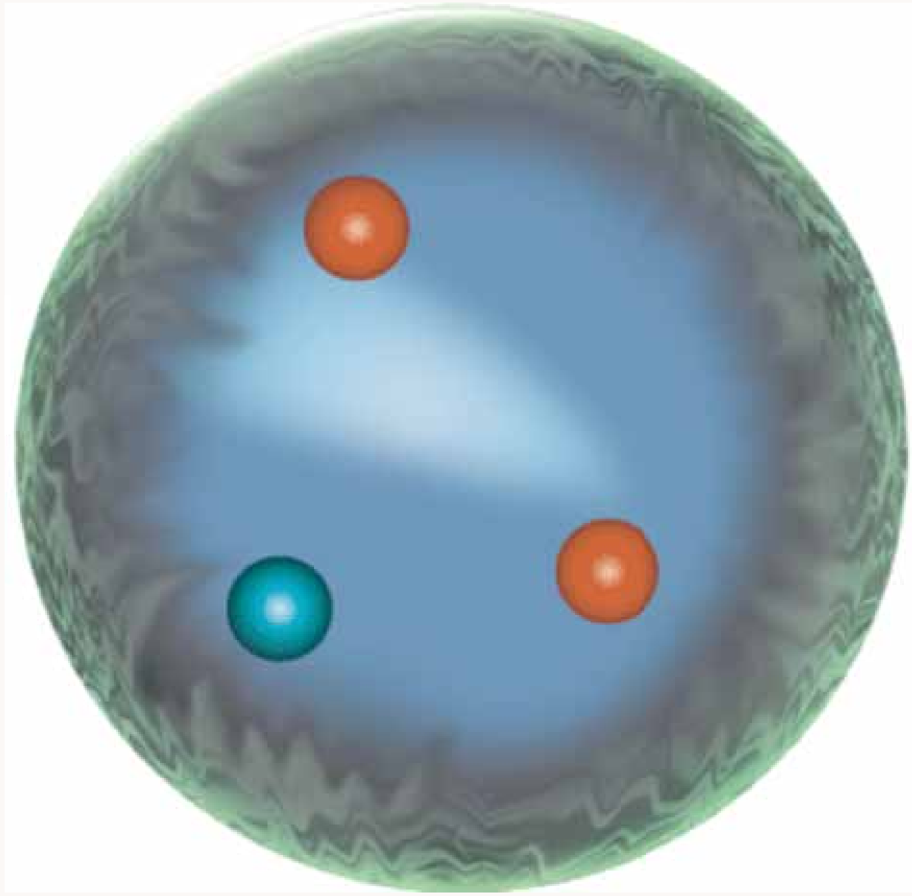
Quarks in the Proton



Feynman & Bjorken:
"Parton" model

Bjorken: Scaling

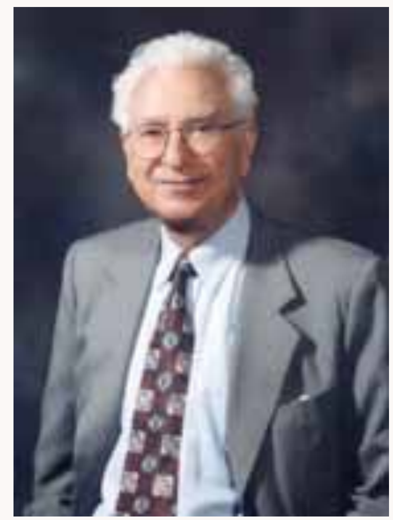
$\mathbf{p} = (u\ u\ d)$



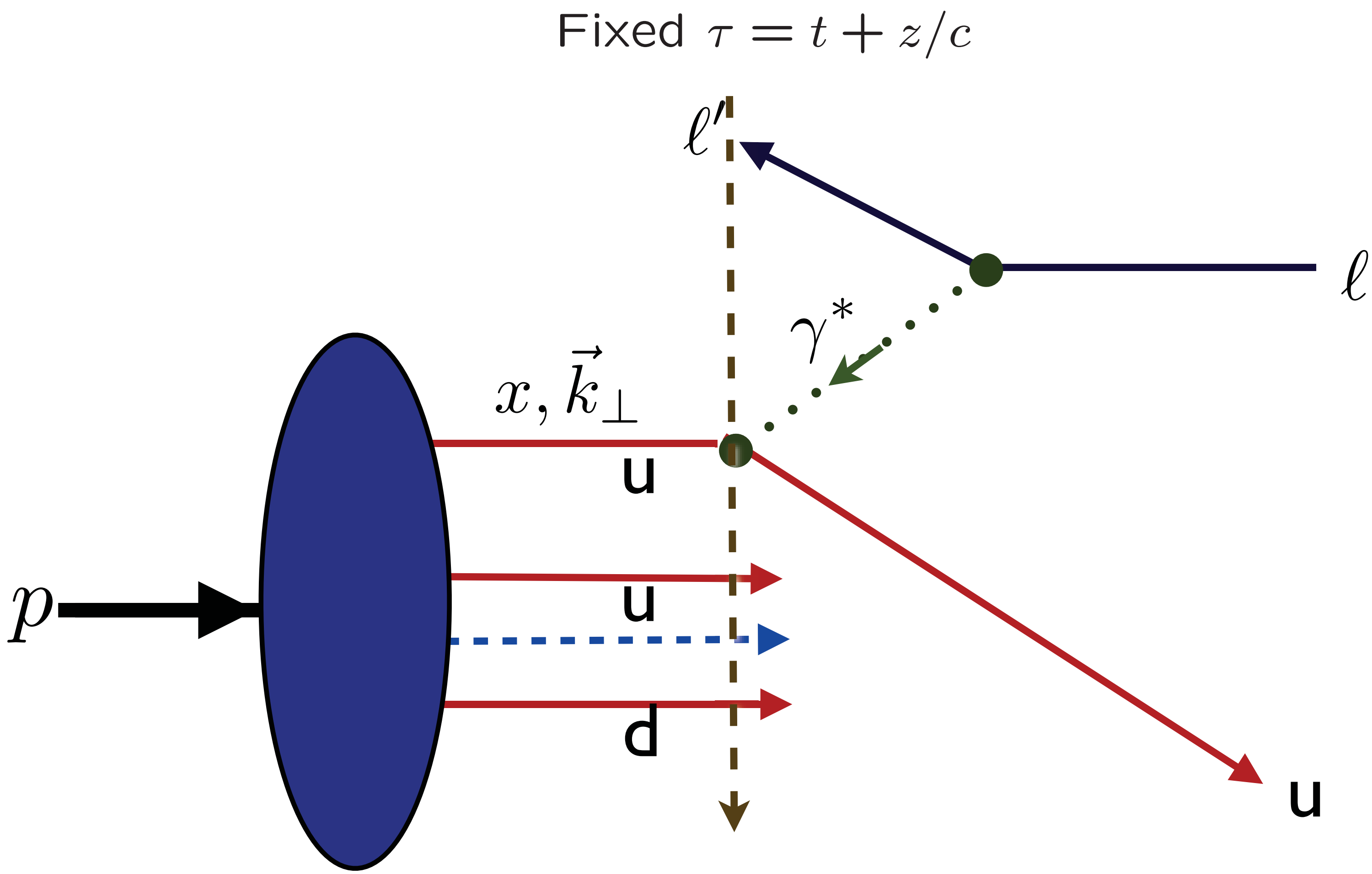
$1\,fm$

$10^{-15}m = 10^{-13}cm$

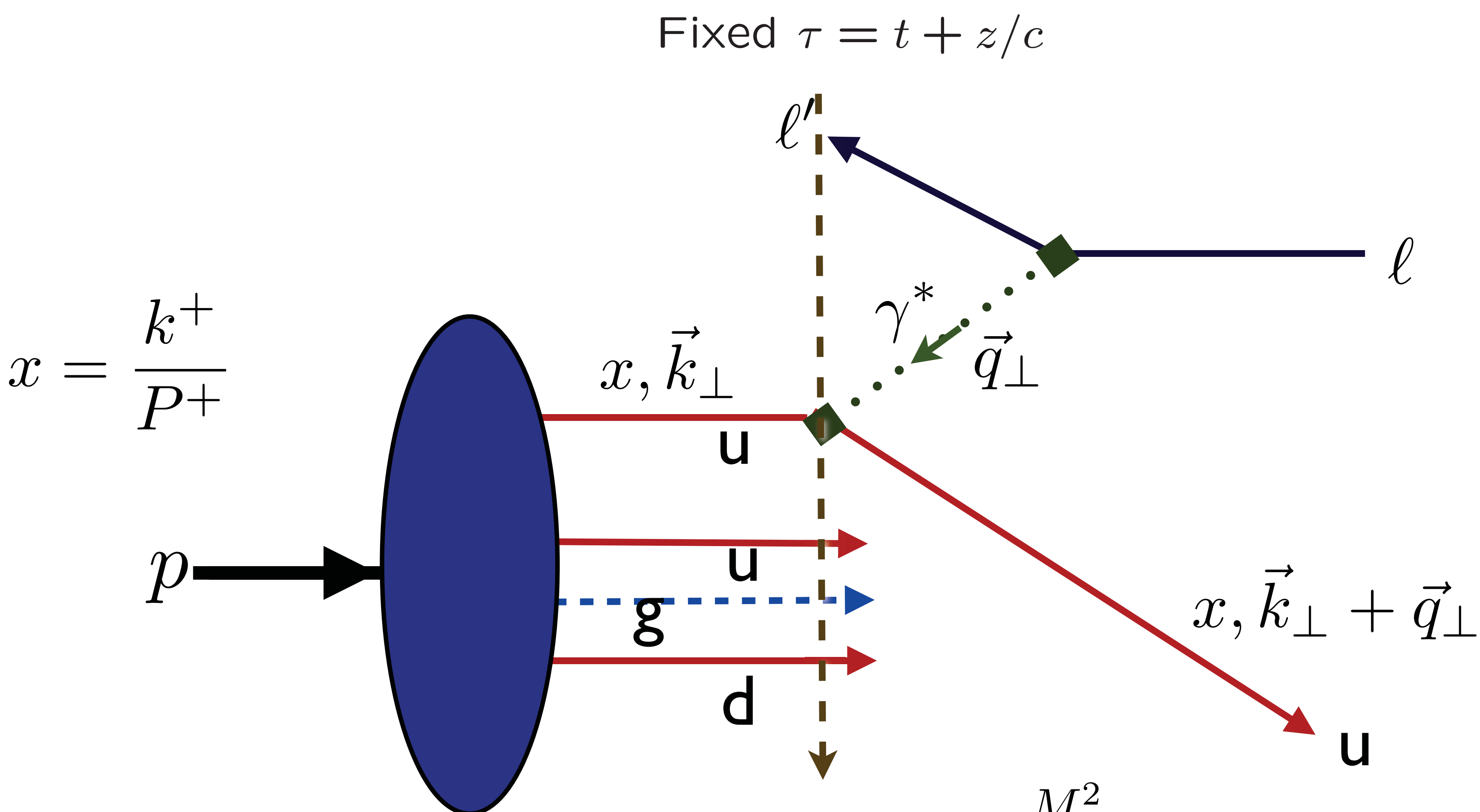
Zweig: "Aces, Deuces, Treys"



Gell Mann: "Three Quarks for Mr. Mark"



$$x = \frac{k^+}{p^+} = \frac{k^0 + k^z}{p^0 + p^z} \simeq x_{bj} = \frac{Q^2}{2p \cdot q}$$



$$p^\mu = (p^+, p^-, \vec{p}_\perp) = (P^+, \frac{M^2}{P^+}, 0_\perp)$$

$$q^\mu = (q^+, q^-, \vec{q}_\perp) = (0, \frac{2q \cdot p}{P^+}, \vec{q}_\perp)$$

$$Q^2 = \vec{q}_\perp^{\,2}$$

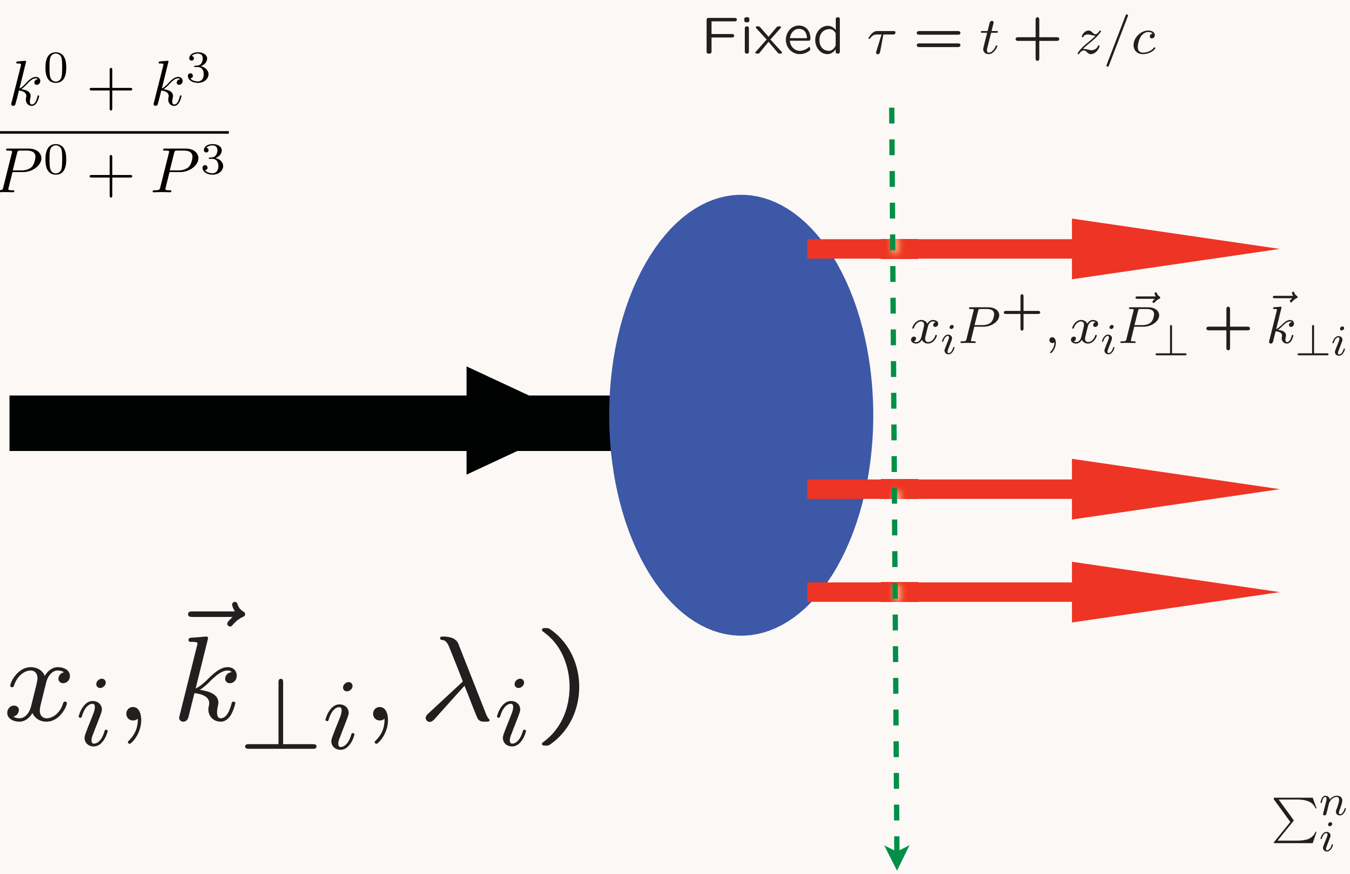
P- conservation $\quad 2q \cdot p + M^2 = \frac{(\vec{k}_\perp + \vec{q}_\perp)^2 + m^2}{x} + \frac{\vec{k}_\perp^2 + M_s^2}{1-x}$

$$x = \frac{Q^2}{2q \cdot p} = x_{bj}$$

plus mass,
transverse momentum
and final-state interaction corrections

Light-Front Wavefunctions: rigorous representation of composite systems in quantum field theory

$$x = \frac{k^+}{P^+} = \frac{k^0 + k^3}{P^0 + P^3}$$



$$\Psi_n(x_i, \vec{k}_{\perp i}, \lambda_i)$$

$\sum_i^n x_i = 1$

$\sum_i^n \vec{k}_{\perp i} = \vec{0}_\perp$

Structure functions and other distributions computed from the square of the LFWFs

Goal: Predict all features from first principles

QCD Lagrangian

Generalization of QED

gluon dynamics — quark kinetic energy + quark-gluon dynamics — mass term

$$L_{QCD} = -\frac{1}{4g^2} Tr(G^{\mu\nu} G_{\mu\nu}) + \sum_{f=1}^{nf} i \overline{\psi_f} D_\mu \gamma^\mu \psi_f + \sum_{f=1}^{nf} m_f \overline{\psi_f} \psi_f$$

QCD color charge — field strength tensor — covariant derivative — quark field

Yang Mills Gauge Principle: Color Rotation and Phase Invariance at Every Point of Space and Time

Scale-Invariant Coupling
Renormalizable
Nearly-Conformal
Asymptotic Freedom
Color Confinement

QED Lagrangian

$$\mathcal{L}_{QED} = -\frac{1}{4} Tr(F^{\mu\nu} F_{\mu\nu}) + \sum_{\ell=1}^{n_\ell} i \bar{\Psi}_\ell D_\mu \gamma^\mu \Psi_\ell + \sum_{\ell=1}^{n_\ell} m_\ell \bar{\Psi}_\ell \Psi_\ell$$

$$iD^\mu = i\partial^\mu - eA^\mu \qquad F^{\mu\nu} = \partial^\mu A^\mu - \partial^\nu A^\mu$$

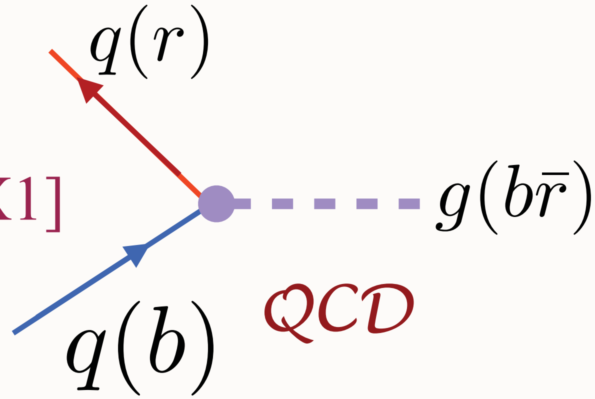
Yang Mills Gauge Principle:
Phase Invariance at Every
Point of Space and Time

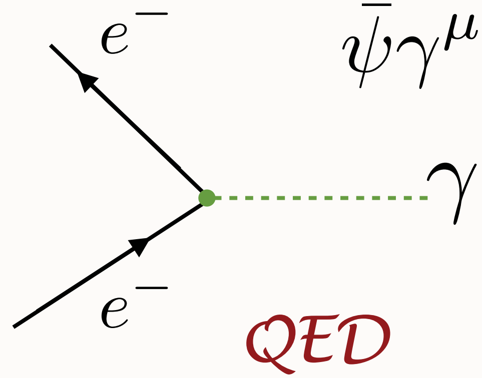
Scale-Invariant Coupling
Renormalizable
Nearly-Conformal
Landau Pole

Fundamental Couplings of QED and QCD

$\bar{\psi}\gamma^{\mu}A^{\mu}\bar{\psi}$

[1X3] [3X3] [3X1]





$\bar{\psi}\gamma^{\mu}A^{\mu}\bar{\psi}$

$$\mathcal{L}_{QCD} = -\frac{1}{4}Tr(G^{\mu\nu}G_{\mu\nu}) + \sum_{f=1}^{n_f} i\bar{\Psi}_f D_{\mu}\gamma^{\mu}\Psi_f + \sum_{f=1}^{n_f} m_f\bar{\Psi}_f\Psi_f$$

$$G^{\mu\nu} = \partial^{\mu}A^{\mu} - \partial^{\nu}A^{\mu} - g[A^{\mu}, A^{\nu}]$$

Gluon vertices

$G^{\mu\nu}G_{\mu\nu}$

gluon self couplings

Angular Momentum on the Light-Front

LC gauge

$$J^z = \sum_{i=1}^{n} s_i^z + \sum_{j=1}^{n-1} l_j^z.$$

Conserved
LF Fock state by Fock State

Gluon orbital angular momentum defined in physical lc gauge

$$l_j^z = -\mathrm{i}\left(k_j^1 \frac{\partial}{\partial k_j^2} - k_j^2 \frac{\partial}{\partial k_j^1}\right)$$

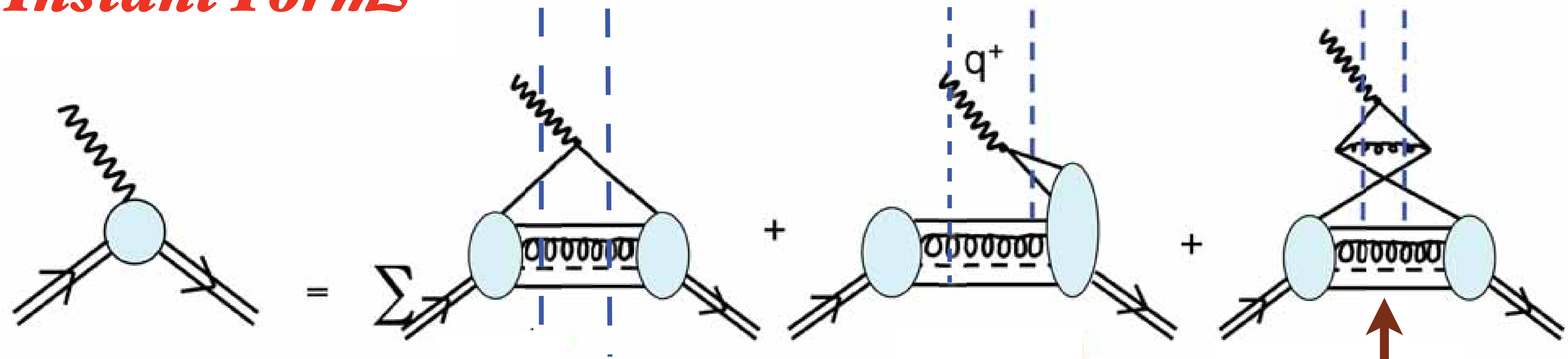
n-1 orbital angular momenta

Orbital Angular Momentum is a property of LFWFS

Nonzero Anomalous Moment -->
Nonzero quark orbital angular momentum!

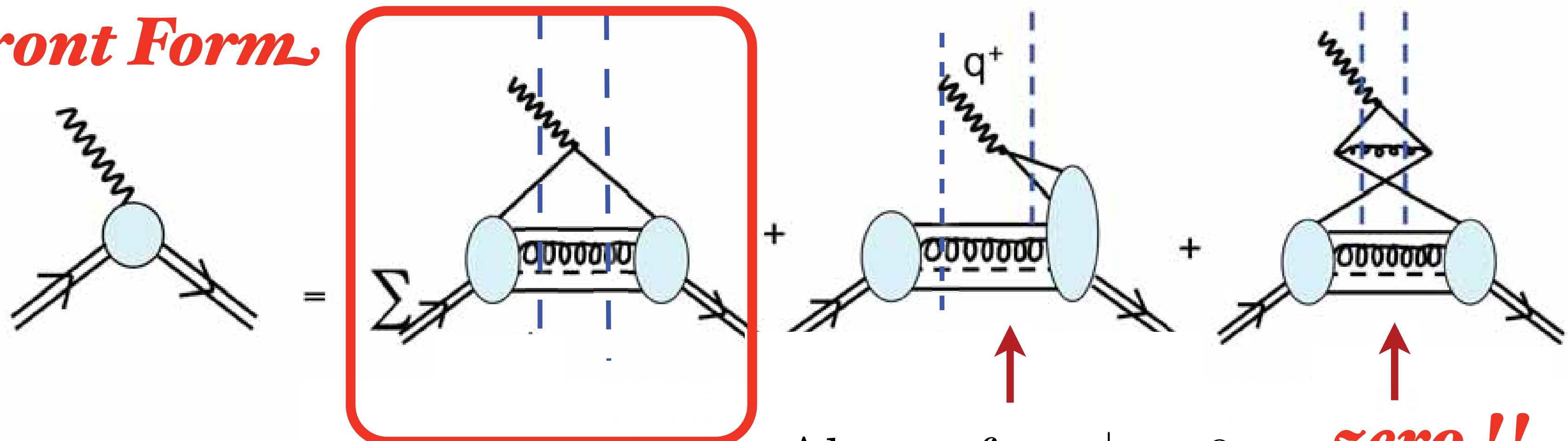
Calculation of Form Factors in Equal-Time Theory

Instant Form



Calculation of Form Factors in Light-Front Theory

Front Form



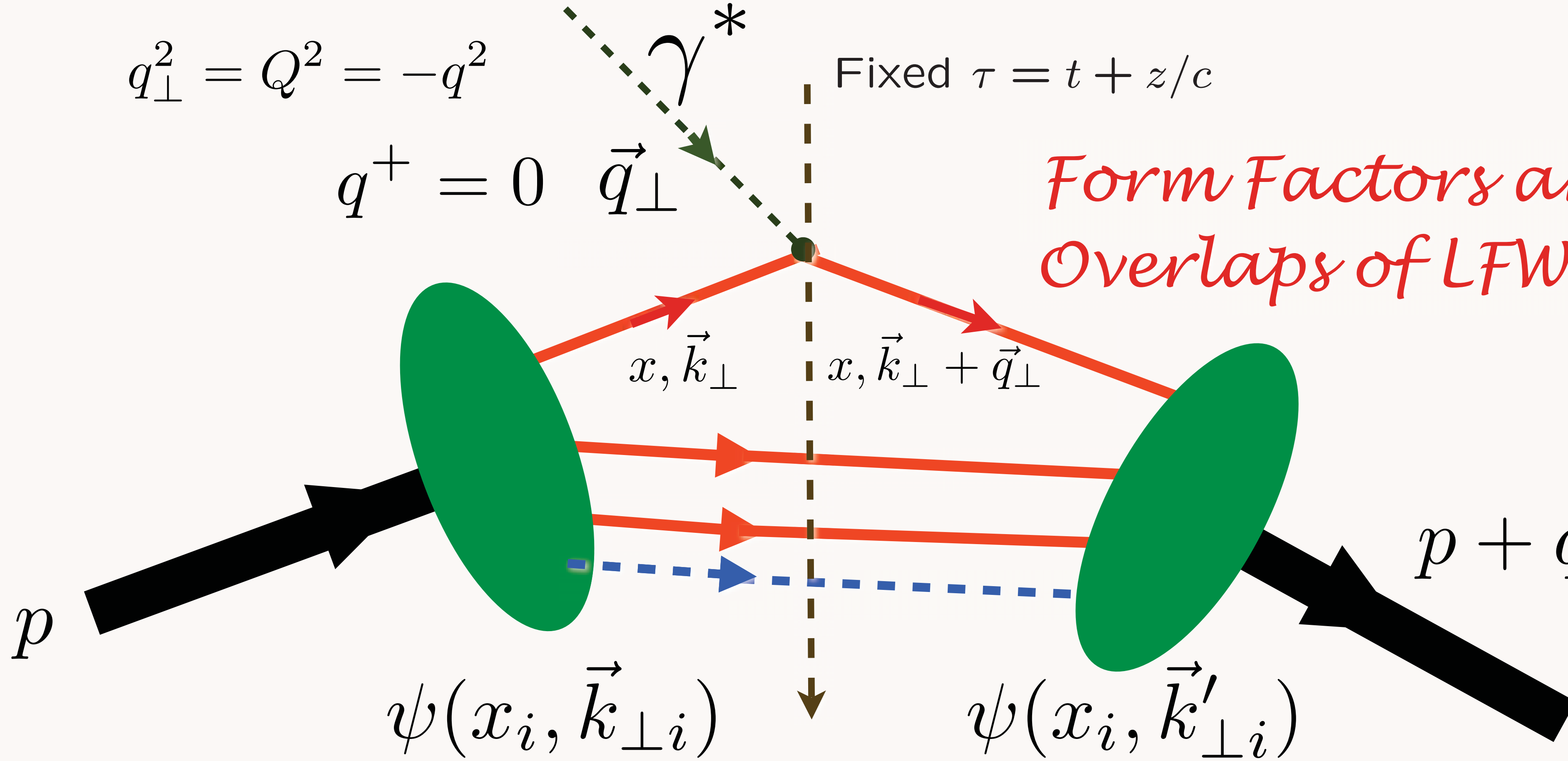
$$< p+q|j^+(0)|p >= 2p^+F(q^2)$$

Interaction picture

$q_\perp^2 = Q^2 = -q^2$

$q^+ = 0 \quad \vec{q}_\perp$

Form Factors are Overlaps of LFWFs



struck $\vec{k}'_{\perp i} = \vec{k}_{\perp i} + (1 - x_i)\vec{q}_\perp$

spectators $\vec{k}'_{\perp i} = \vec{k}_{\perp i} - x_i\vec{q}_\perp$

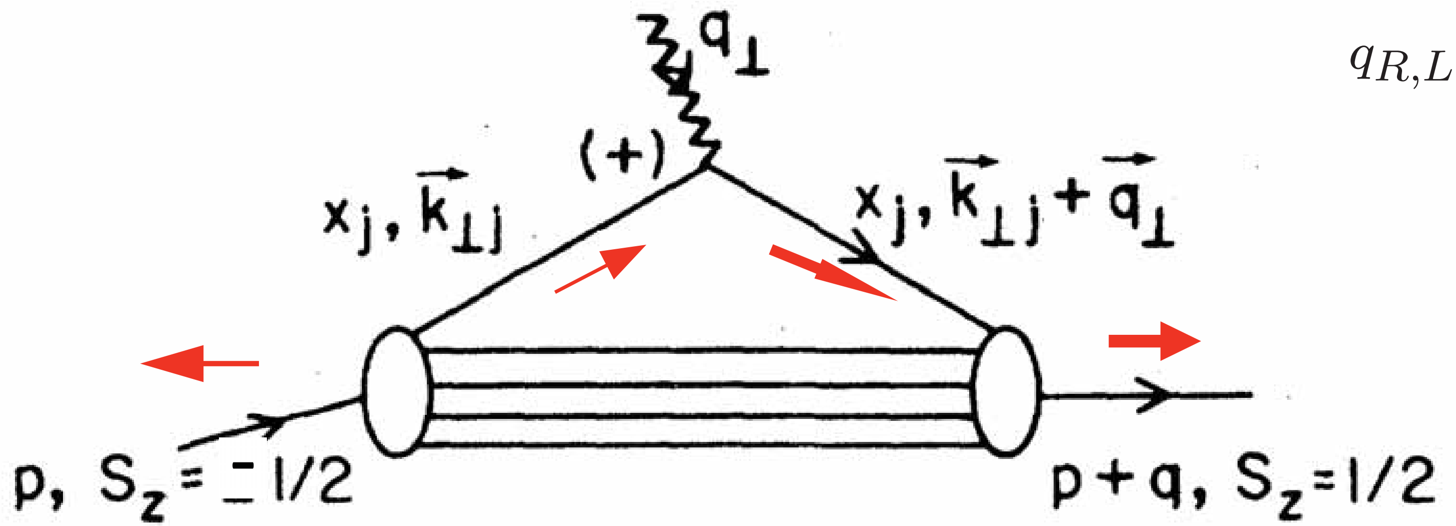
Drell &Yan, West

$$\frac{F_2(q^2)}{2M} = \sum_a \int [\mathrm{d}x][\mathrm{d}^2\mathbf{k}_\perp] \sum_j e_j \, \frac{1}{2} \times$$

Drell, sjb

$$\left[-\frac{1}{q^L} \psi_a^{\uparrow *}(x_i, \mathbf{k}'_{\perp i}, \lambda_i)\, \psi_a^{\downarrow}(x_i, \mathbf{k}_{\perp i}, \lambda_i) + \frac{1}{q^R} \psi_a^{\downarrow *}(x_i, \mathbf{k}'_{\perp i}, \lambda_i)\, \psi_a^{\uparrow}(x_i, \mathbf{k}_{\perp i}, \lambda_i) \right]$$

$$\mathbf{k}'_{\perp i} = \mathbf{k}_{\perp i} - x_i \mathbf{q}_\perp \qquad \mathbf{k}'_{\perp j} = \mathbf{k}_{\perp j} + (1 - x_j)\mathbf{q}_\perp$$



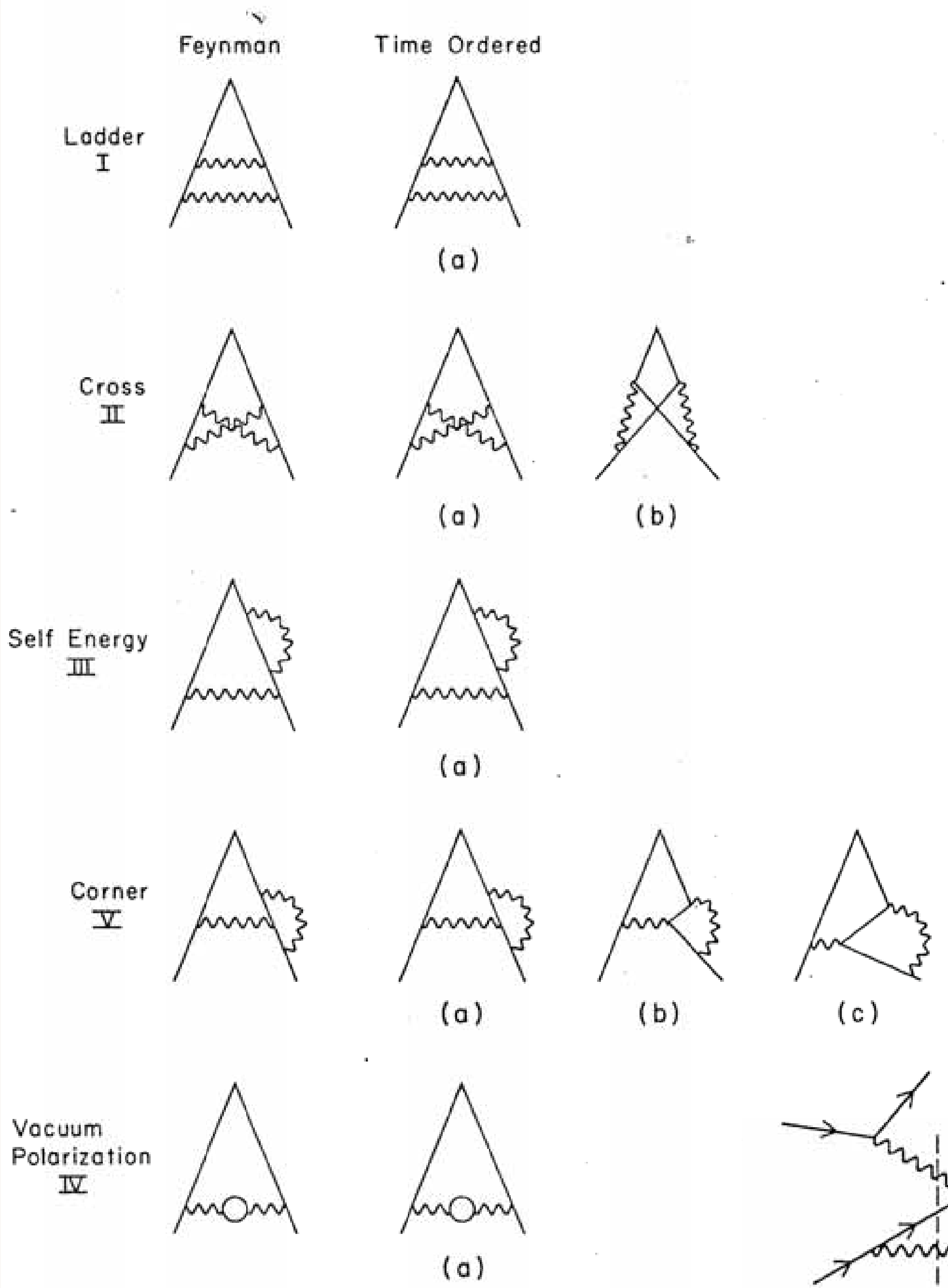
$$q_{R,L} = q^x \pm i q^y$$

Must have $\Delta \ell_z = \pm 1$ to have nonzero $F_2(q^2)$

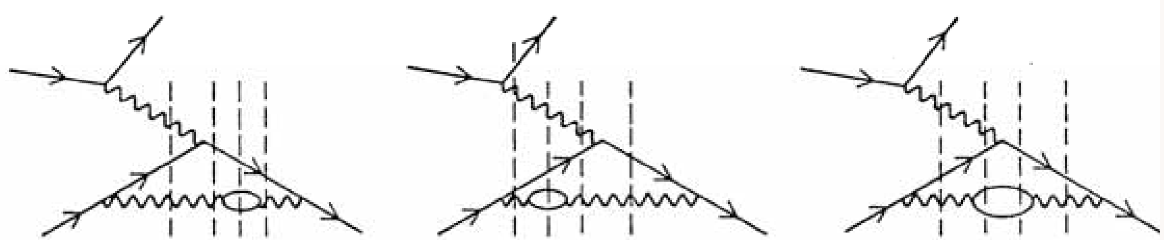
Nonzero Proton Anomalous Moment -->
Nonzero orbital quark angular momentum

QED g-2 in LFPth

Roskies, Suaya, and sjb

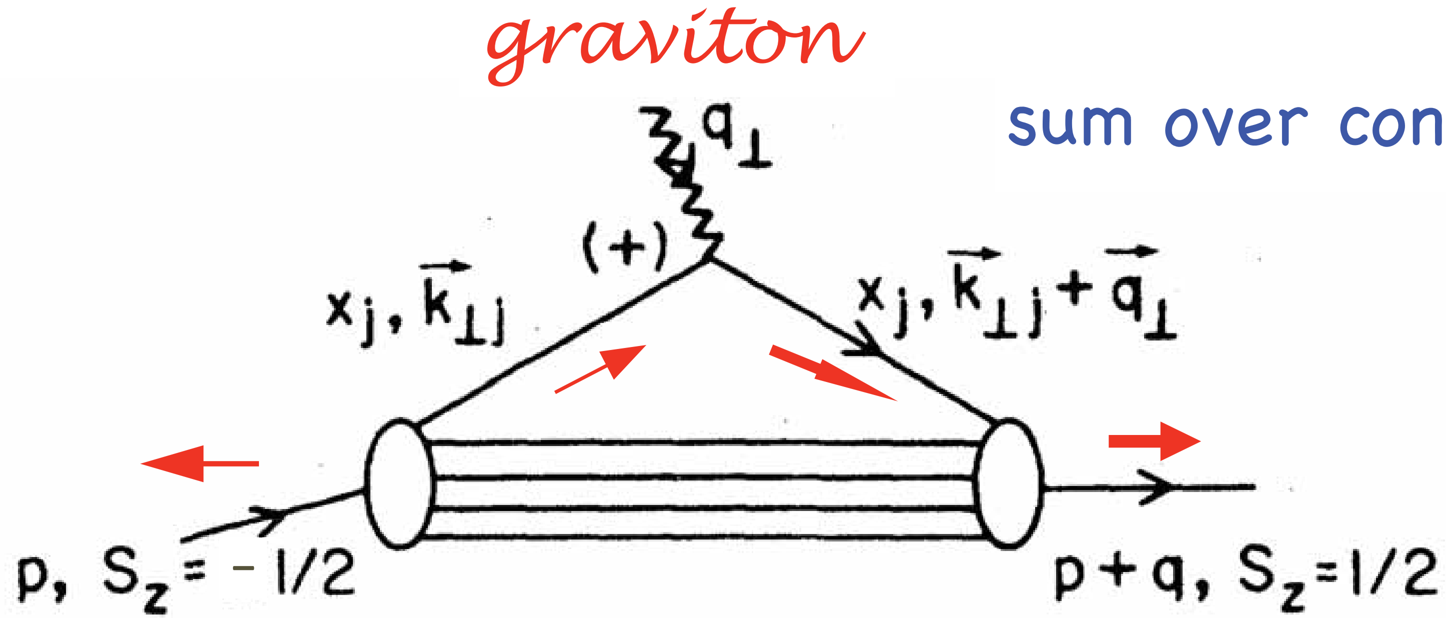


Alternate denominator renormalization



Anomalous gravitomagnetic moment B(0)

Terayev, Okun, et al: *B(0) Must vanish because of Equivalence Theorem*



sum over constituents

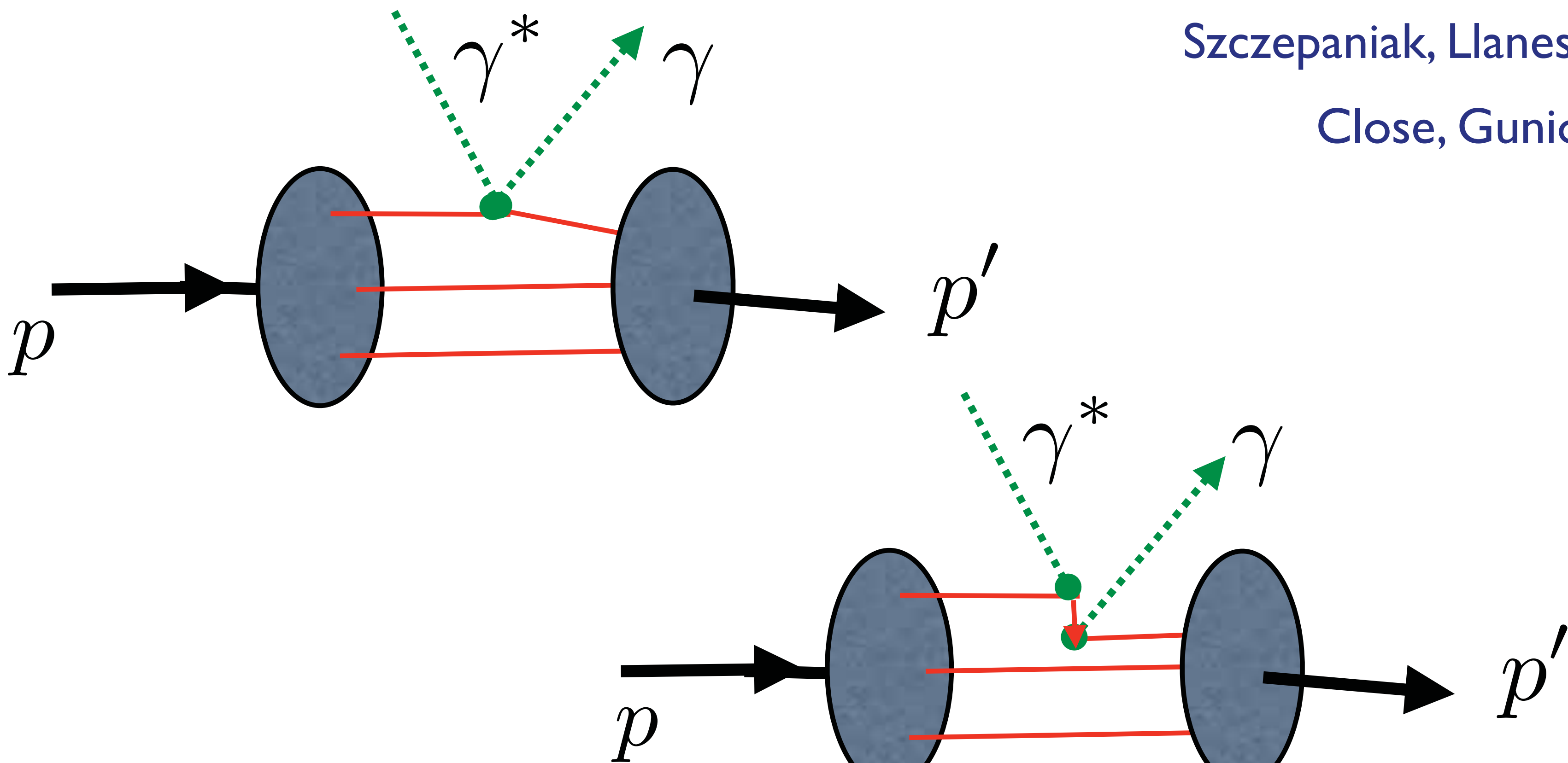
Hwang, Schmidt, sjb; Holstein et al

$B(0) = 0$

Each Fock State

J=0 Fixed Pole Contribution to DVCS

- J=0 fixed pole -- direct test of QCD locality -- from seagull or instantaneous contribution to Feynman propagator



Szczepaniak, Llanes-Estrada, sjb

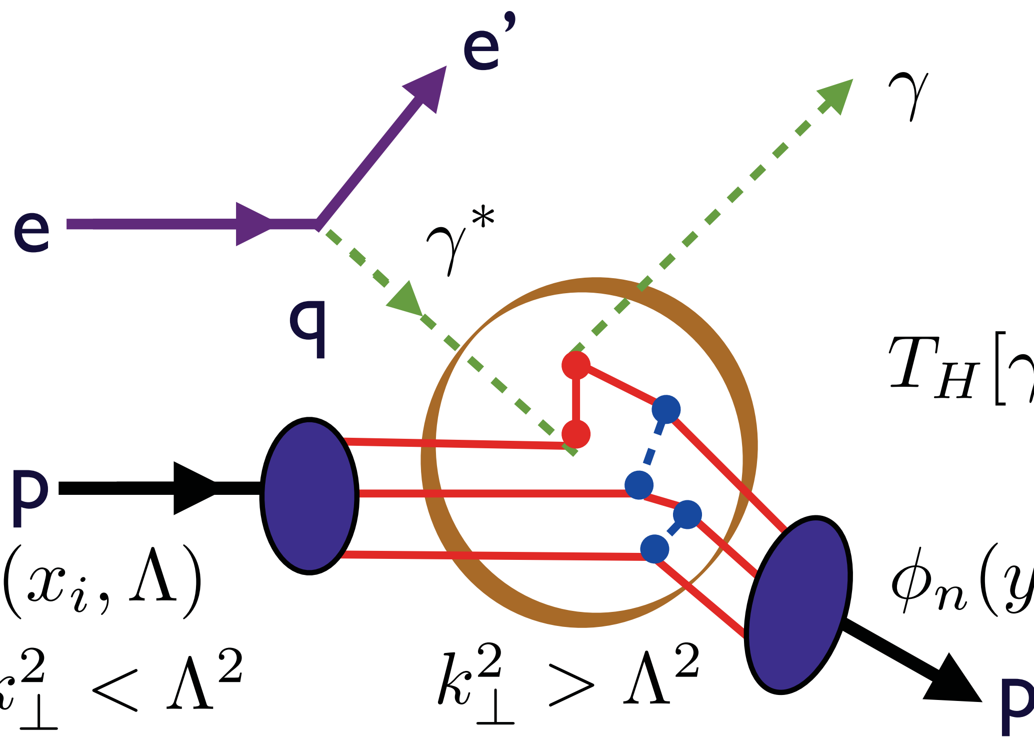
Close, Gunion, sjb

Real amplitude, independent of Q^2 at fixed t

QCD Factorization
DVCS in hard-scattering domain

Lepage, sjb

$$ep \to e'\gamma p$$



$$T_H[\gamma^* + (uud) \to \gamma + (uud)]$$

$\phi_p(x_i, \Lambda)$ $\qquad$ $\phi_n(y_i, \Lambda)$

$k_\perp^2 < \Lambda^2$ $\qquad$ $k_\perp^2 > \Lambda^2$

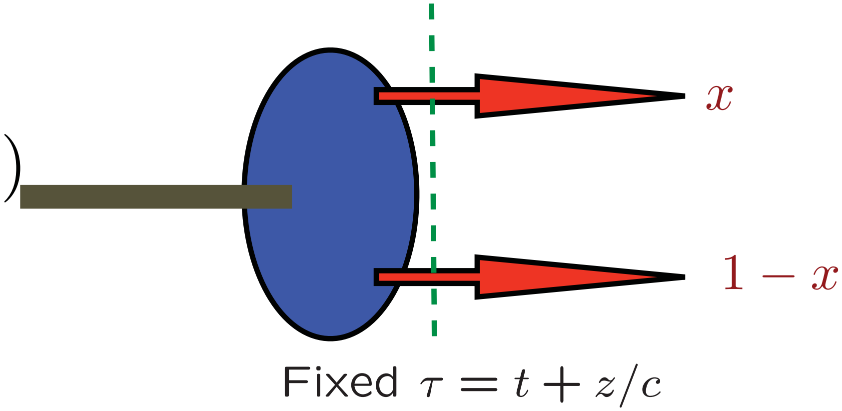
$$T = \int_0^1 dx \int_0^1 dy \int_0^1 dx\ \phi_p(x,\Lambda) T_H(x,y,z;Q^2,s,t;\Lambda)\phi_n(y,\Lambda)\phi_\pi^+(z,\Lambda)$$

Universal distribution amplitudes.
Renormalization Group Invariance:
Renormalization scale is unambiguous -- BLM

J=0 Fixed pole from instantaneous gluon

Hadron Distribution Amplitudes

$$\phi_M(x,Q) = \int^Q d^2\vec{k}\ \psi_{q\bar{q}}(x,\vec{k}_\perp)$$



$k_\perp^2 < Q^2$

$$\sum_i x_i = 1$$

- Fundamental gauge invariant non-perturbative input to hard exclusive processes, heavy hadron decays. Defined for Mesons, Baryons

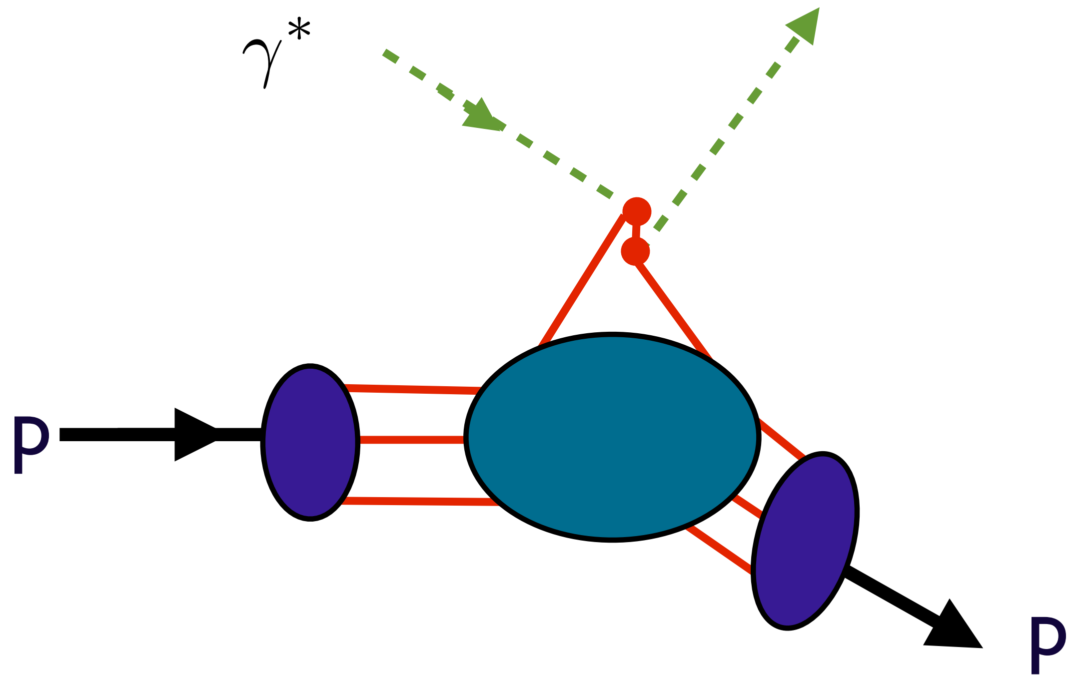
Lepage, sjb

- Evolution Equations from PQCD, OPE
- Conformal Invariance
- Compute from valence light-front wavefunction in light-cone gauge

Lepage, sjb
Efremov, Radyushkin
Sachrajda, Frishman Lepage, sjb
Braun, Gardi

Deeply Virtual Compton Scattering

$$\gamma^* p \to \gamma p$$



Seagull interaction (instantaneous quark exchange or Z-graph)

$$s >> -t, Q^2 >> \Lambda^2_{QCD}$$

Hard Reggeon Domain

$$T(\gamma^*(q)p \to \gamma(k) + p) \sim \epsilon \cdot \epsilon' \sum_R s^{\alpha}_R(t)\beta_R(t)$$

$$\alpha_R(t) \to 0$$

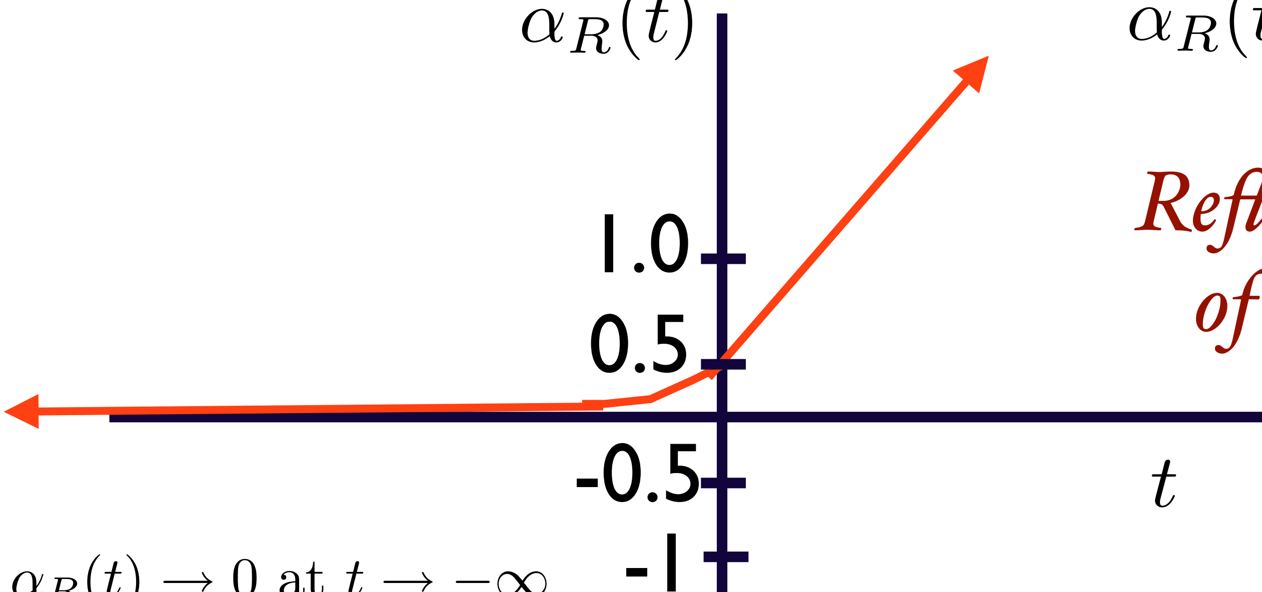
Reflects elementary coupling of two photons to quarks

$$\beta_R(t) \sim \frac{1}{t^2}$$

$$\frac{d\sigma}{dt} \sim \frac{1}{s^2}\frac{1}{t^4} \sim \frac{1}{s^6} \text{ at fixed } \frac{Q^2}{s}, \frac{t}{s}$$

Regge domain

$$T(\gamma^* p \to \pi^+ n) \sim \epsilon \cdot p_i \sum_R s_R^{\alpha}(t) \beta_R(t) \qquad s >> -t, Q^2$$



$\alpha_R(t) \to 0$ at $t \to -\infty$

$\alpha_R(t) \to 0$ at $t \to -\infty$

J=0 fixed pole

Reflects elementary couplin

of two photons to quarks

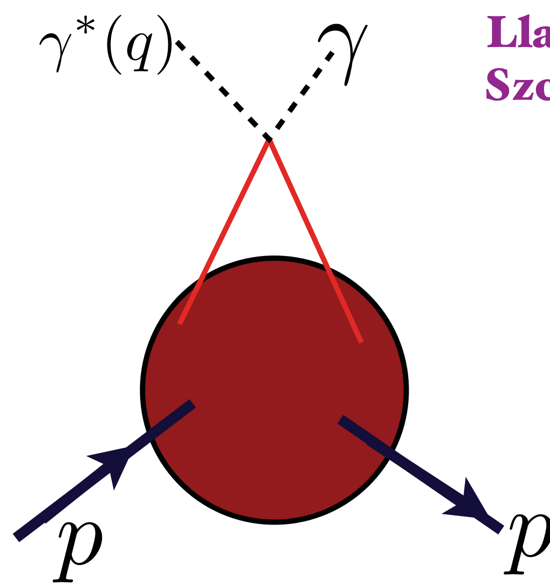
$$\beta_R(t) \sim \frac{1}{t^2}$$

$$\frac{d\sigma}{dt}(\gamma^* p \to \gamma p) \to \frac{1}{s^2} \beta_R^2(t) \sim \frac{1}{s^2 t^4} \sim \frac{1}{s^6} \text{ at fixed } \frac{t}{s}, \frac{Q^2}{s}$$

Fundamental test of QCD

J=0 Fixed pole in real and virtual Compton scattering

Damashek, Gilman
Close, Gunion, sjb
Llanes-Estrada,
Szczepaniak, sjb



Effective two-photon contact term

Seagull for scalar quarks

Real phase

$$M = s^0 \sum e_q^2 F_q(t)$$

Independent of Q^2 at fixed t

<1/x> Moment: Related to Feynman-Hellman Theorem

Fundamental test of local gauge theory

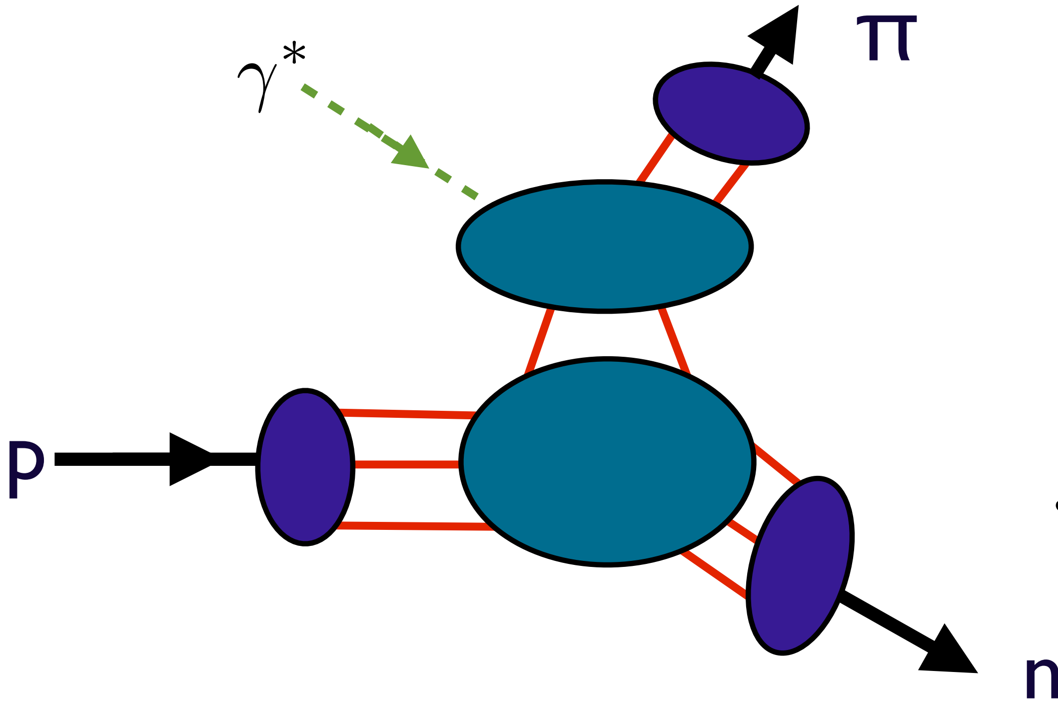
No ambiguity in D-term

Q^2-independent contribution to Real DVCS amplitude

$$s^2 \frac{d\sigma}{dt}(\gamma^* p \to \gamma p) = F^2(t)$$

Exclusive Electroproduction

$$ep \to e'\pi^+ n$$



Hard Reggeon Domain

$$s >> -t, Q^2 >> \Lambda^2_{QCD}$$

$$T(\gamma^* p \to \pi^+ n) \sim \epsilon \cdot p_i \sum_R s_R^{\alpha}(t) \beta_R(t)$$

$$\alpha_R(t) \to -1$$

Reflects elementary exchange of quarks in t-channel

$$\beta_R(t) \sim \frac{1}{t^2}$$

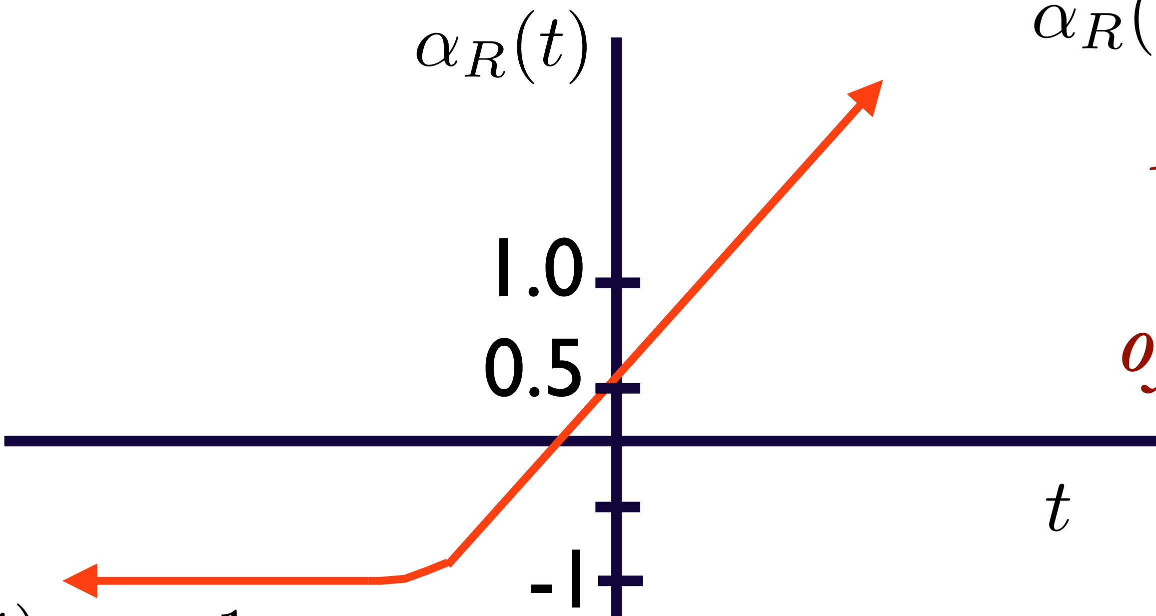
$$\frac{d\sigma}{dt} \sim \frac{1}{s^7} \text{ at fixed } \frac{Q^2}{s}, \frac{t}{s}$$

Gunion, Blankenbecler, Savit, sjb

Regge domain

$$T(\gamma^* p \to \pi^+ n) \sim \epsilon \cdot p_i \sum_R s_R^{\alpha}(t)\beta_R(t) \qquad s >> -t, Q^2$$

$\alpha_R(t) \to -1$ at $t \to -\infty$



Reflects elementary exchange of quarks in t-channel

$\alpha_R(t) \to -1$

$$\beta_R(t) \sim \frac{1}{t^2}$$

$$\frac{d\sigma}{dt}(\gamma^* p \to \pi^+ n) \to \frac{1}{s^3}\beta_R^2(t)$$

$$\frac{d\sigma}{dt} \sim \frac{1}{s^3}\frac{1}{t^4} \sim \frac{1}{s^7} \text{ at fixed } \frac{Q^2}{s}, \frac{t}{s}$$

Fundamental test of QCD

$$|p, S_z> = \sum_{n=3} \Psi_n(x_i, \vec{k}_{\perp i}, \lambda_i)|n; \vec{k}_{\perp_i}, \lambda_i>$$

sum over states with n=3, 4, ...constituents

The Light Front Fock State Wavefunctions

$$\Psi_n(x_i, \vec{k}_{\perp i}, \lambda_i)$$

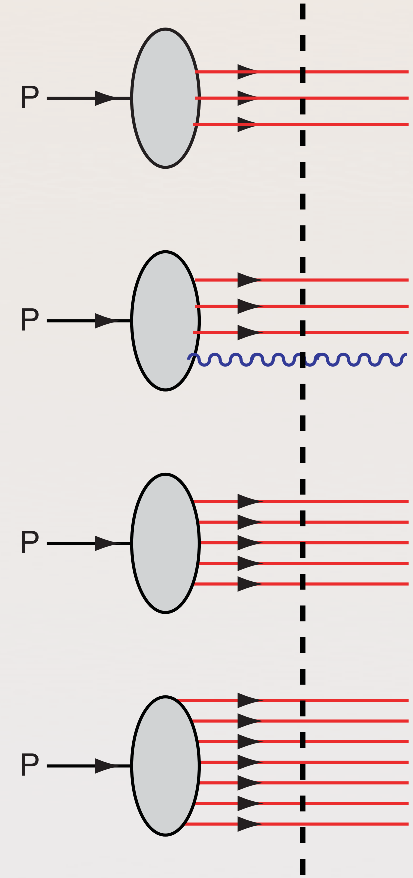
are boost invariant; they are independent of the hadron's energy and momentum P^μ.

The light-cone momentum fraction

$$x_i = \frac{k_i^+}{p^+} = \frac{k_i^0 + k_i^z}{P^0 + P^z}$$

are boost invariant.

$$\sum_i^n k_i^+ = P^+, \ \sum_i^n x_i = 1, \ \sum_i^n \vec{k}_i^\perp = \vec{0}^\perp.$$



Fixed LF time

Intrinsic heavy quarks

c(x), b(x) at high x !

$\bar{s}(x) \neq s(x)$

$\bar{u}(x) \neq \bar{d}(x)$

Mueller: gluon Fock states → BFKL Pomeron

Hidden Color

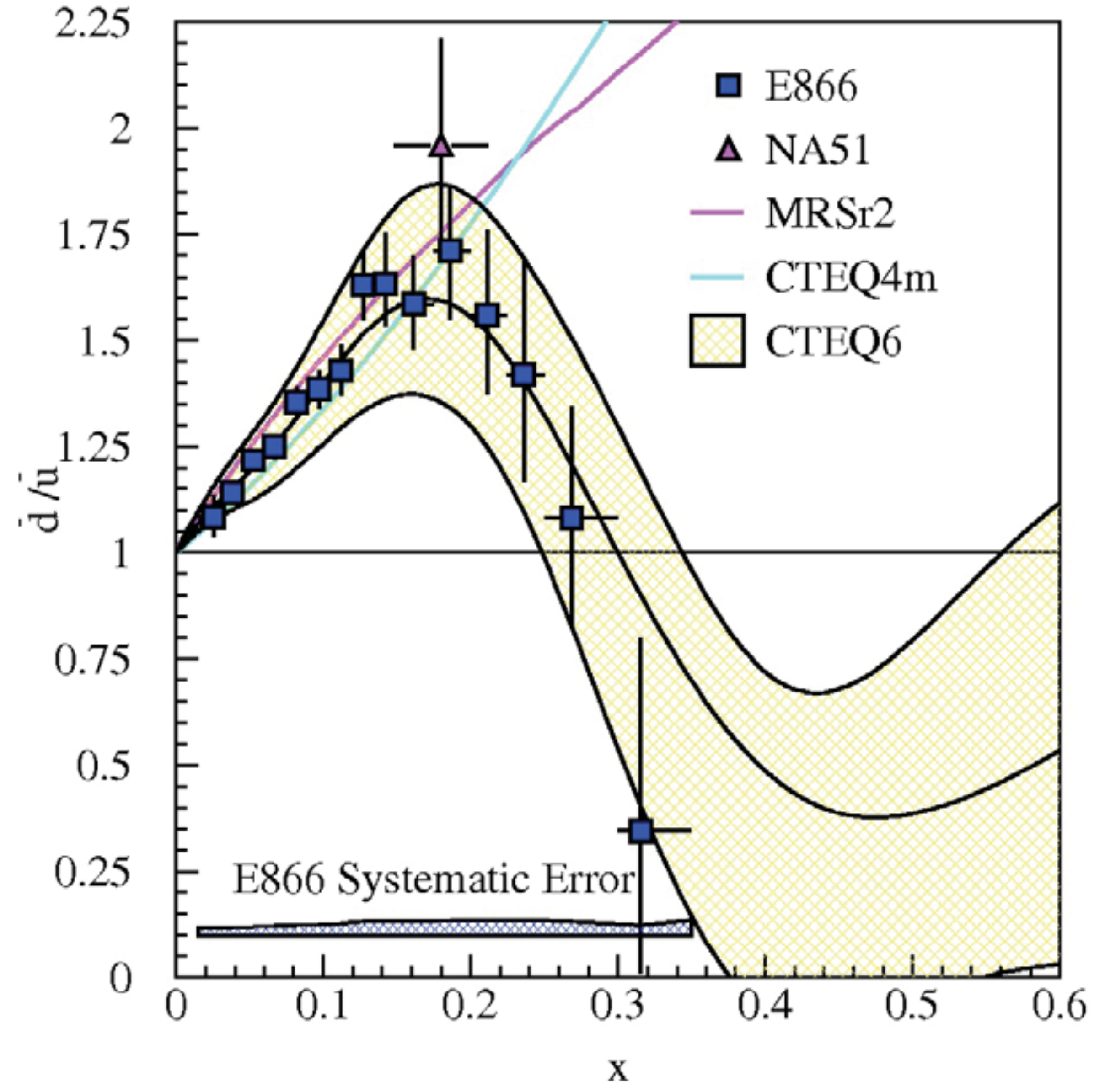
- E866/NuSea (Drell-Yan)

$$\bar{d}(x) \neq \bar{u}(x)$$

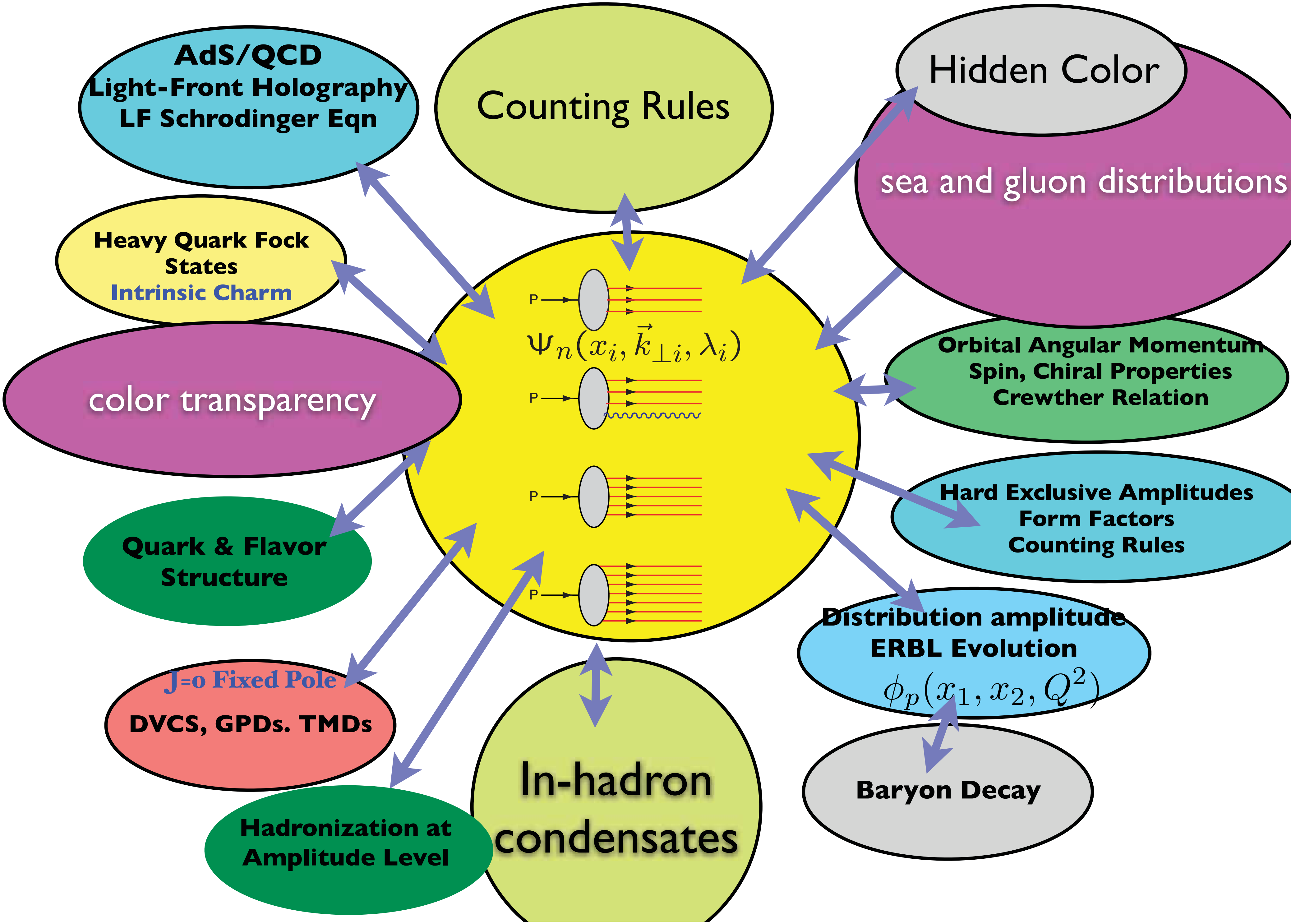
$$s(x) \neq \bar{s}(x)$$

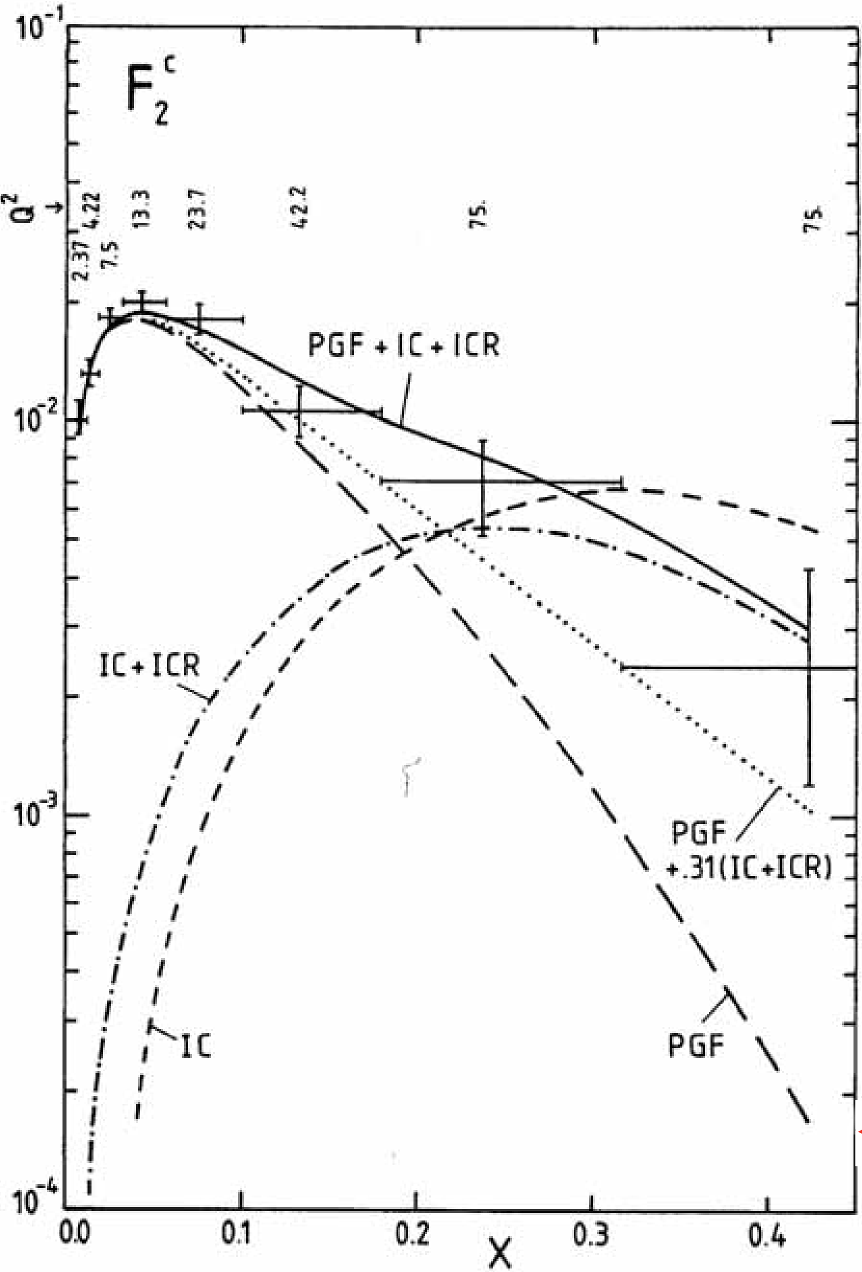
Intrinsic glue, sea, heavy quarks

$\bar{d}(x)/\bar{u}(x)$ for $0.015 \leq x \leq 0.35$



QCD and the LF Hadron Wavefunctions





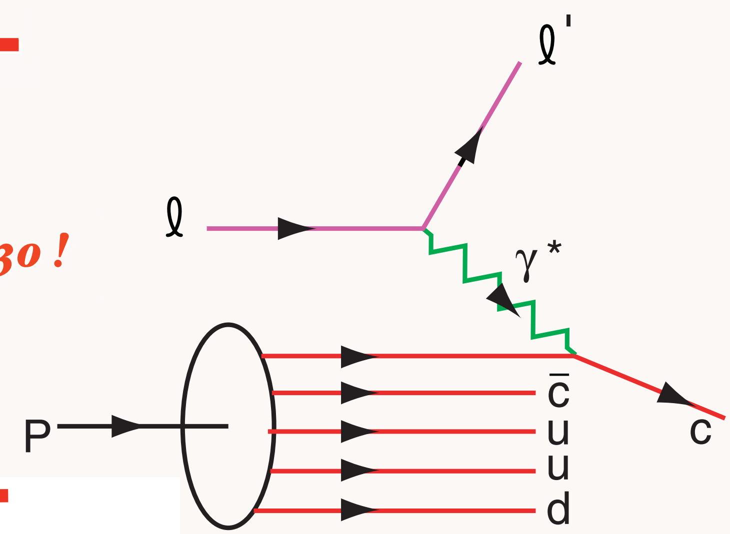
Measurement of Charm Structure Function

J. J. Aubert et al. [European Muon Collaboration], "Production Of Charmed Particles In 250-Gev Mu+ - Iron Interactions," Nucl. Phys. B 213, 31 (1983).

First Evidence for Intrinsic Charm

Never been checked!

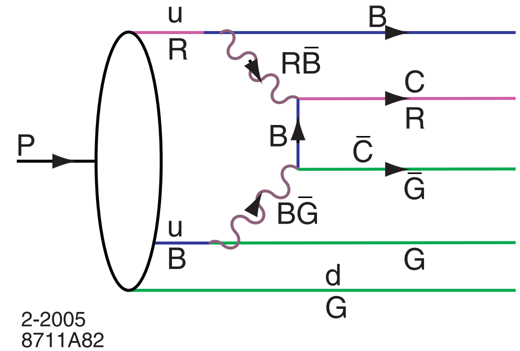
factor of 30 !



DGLAP / Photon-Gluon Fusion: factor of 30 too small

Hoyer, Peterson, Sakai, sjb

Intrinsic Heavy-Quark Fock States



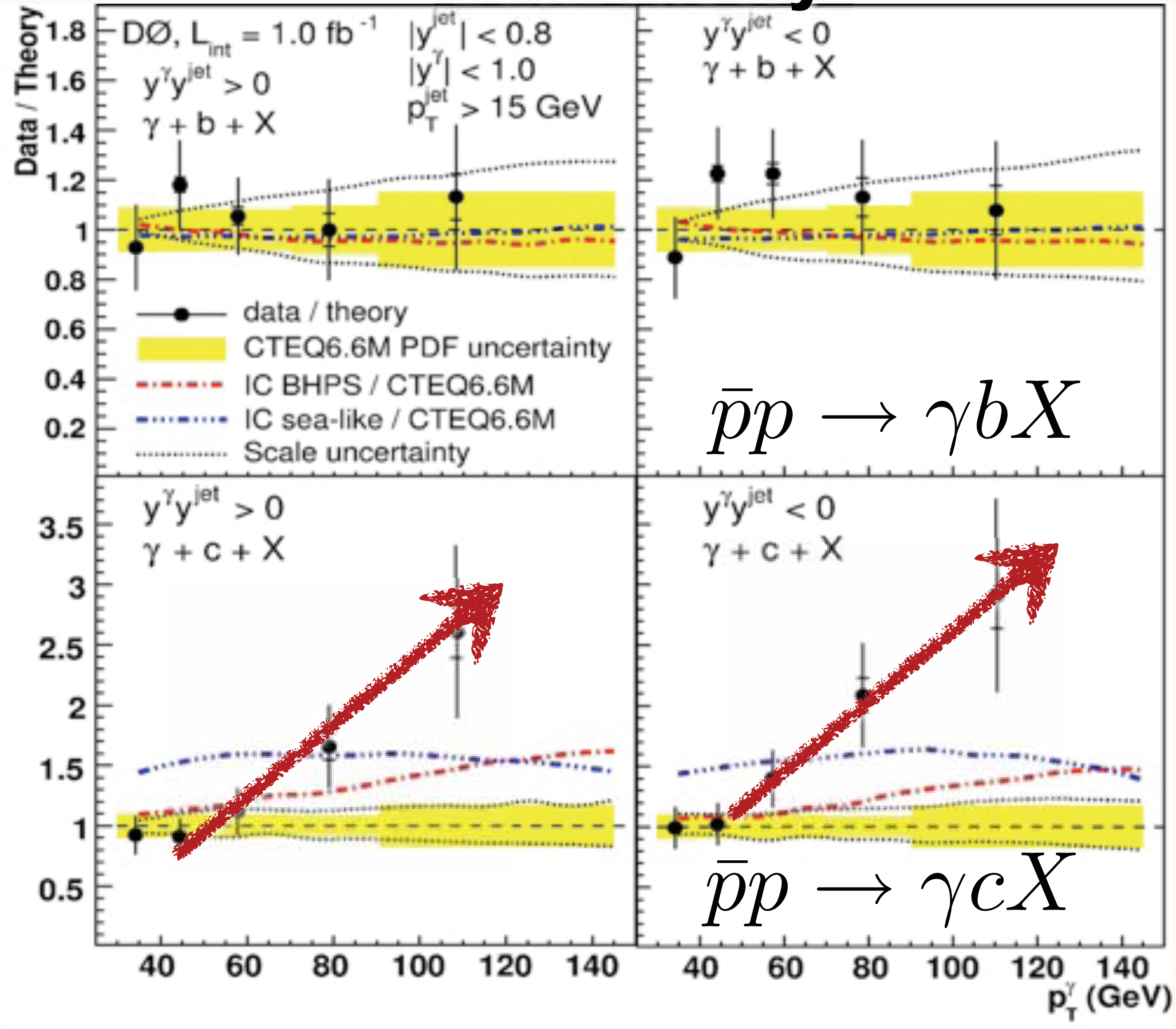
- Rigorous prediction of QCD, OPE
- Color-Octet Color-Octet Fock State!
- Probability $P_{Q\bar{Q}} \propto \frac{1}{M_Q^2}$ $P_{Q\bar{Q}Q\bar{Q}} \sim \alpha_s^2 P_{Q\bar{Q}}$ $P_{c\bar{c}/p} \simeq 1\%$
- Large Effect at high x
- Greatly increases kinematics of colliders such as Higgs production (Kopeliovich, Schmidt, Soffer, sjb)
- Severely underestimated in conventional parameterizations of heavy quark distributions (Pumplin, Tung)
- Many empirical tests

M. Polyakov et al.

OPE

Measurement of $\gamma + b + X$ and $\gamma + c + X$ Production Cross Sections in $p\bar{p}$ Collisions at $\sqrt{s} = 1.96$ TeV

Data/Theory



$$\frac{\Delta\sigma(\bar{p}p \to \gamma c X)}{\Delta\sigma(\bar{p}p \to \gamma b X)}$$

Ratio insensitive to gluon PDF, scales

Signal for significant IC at x > 0.1

- EMC data: $c(x,Q^2) > 30 \times$ DGLAP
  $Q^2 = 75$ GeV^2, $x = 0.42$

- High x_F $pp \to J/\psi X$

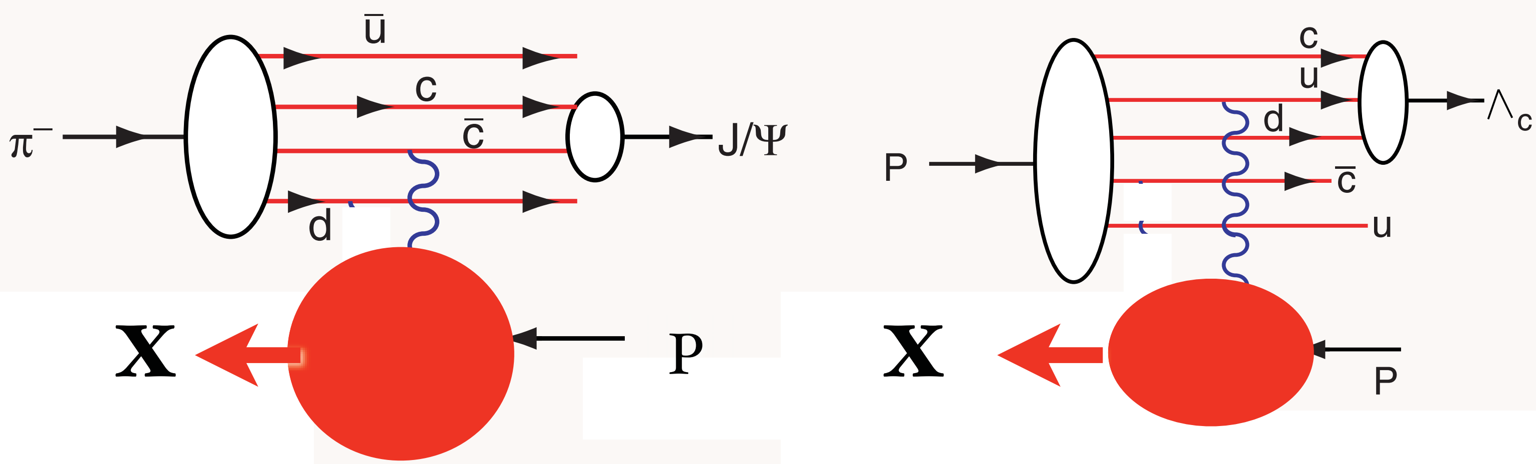
- High x_F $pp \to J/\psi J/\psi X$

- High x_F $pp \to \Lambda_c X$ ISR

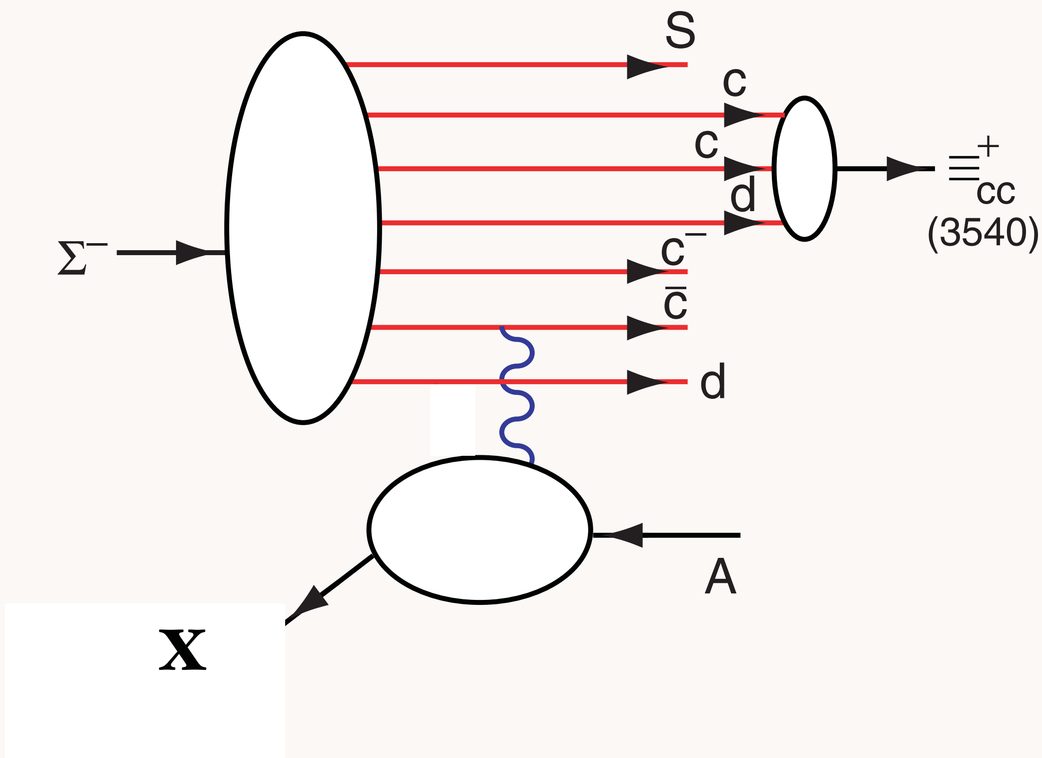
- High x_F $pp \to \Lambda_b X$ ISR

- High x_F $pp \to \Xi(ccd) X$ (SELEX)

Leading Hadron Production from Intrinsic Charm



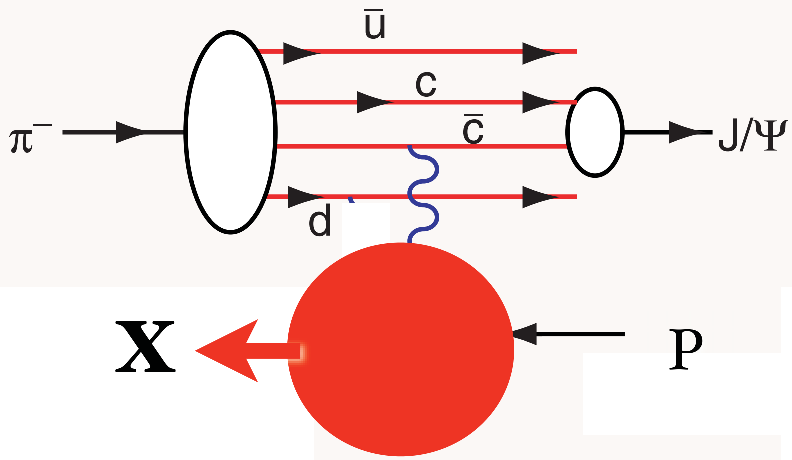
Coalescence of Comoving Charm and Valence Quarks
Produce J/ψ, Λ_c and other Charm Hadrons at High x_F

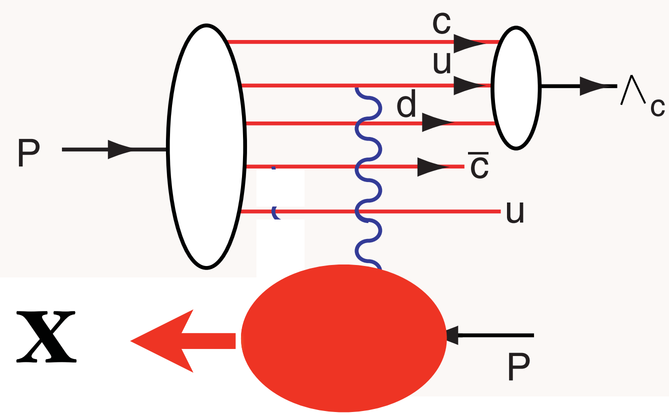


Production of a Double-Charm Baryon

SELEX high x_F $< x_F >= 0.33$

Leading Hadron Production from Intrinsic Charm





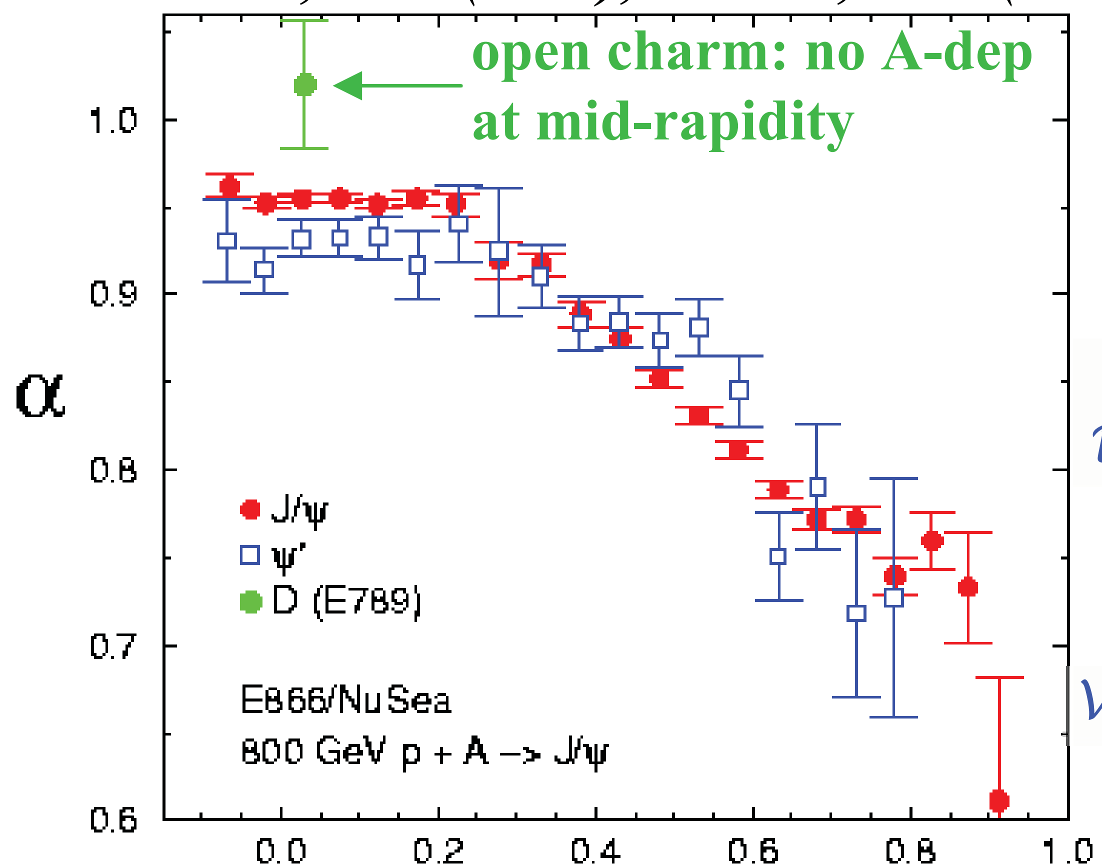
Coalescence of Comoving Charm and Valence Quarks Produce J/ψ, Λ_c and other Charm Hadrons at High x_F

800 GeV p-A (FNAL) $\sigma_A = \sigma_p * A^\alpha$

PRL 84, 3256 (2000); PRL 72, 2542 (1994)

M. Leitch

$$\frac{d\sigma}{dx_F}(pA \to J/\psi X)$$



$X_F = x_1 - x_2$

Remarkably Strong Nuclear Dependence for Fast Charmonium

Violation of PQCD Factorization!

Violation of factorization in charm hadroproduction.

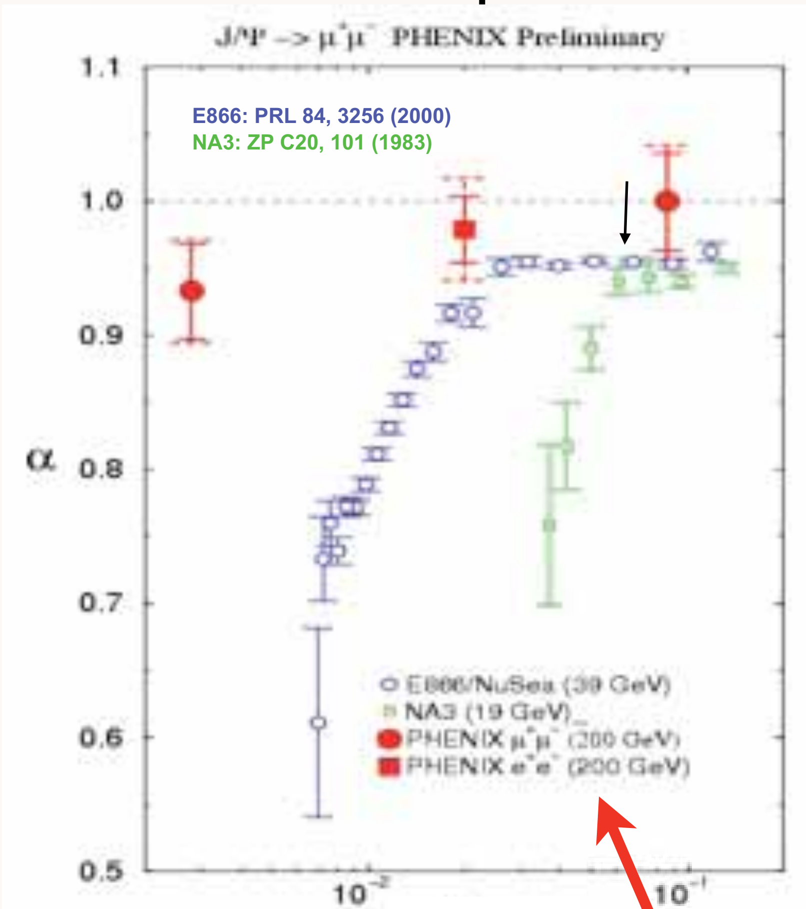
P. Hoyer, **M. Vanttinen** (**Helsinki U.**) , **U. Sukhatme** (**Illinois U., Chicago**) . **HU-TFT-90-14, May 1990. 7pp.**

Published in Phys.Lett.B246:217-220,1990

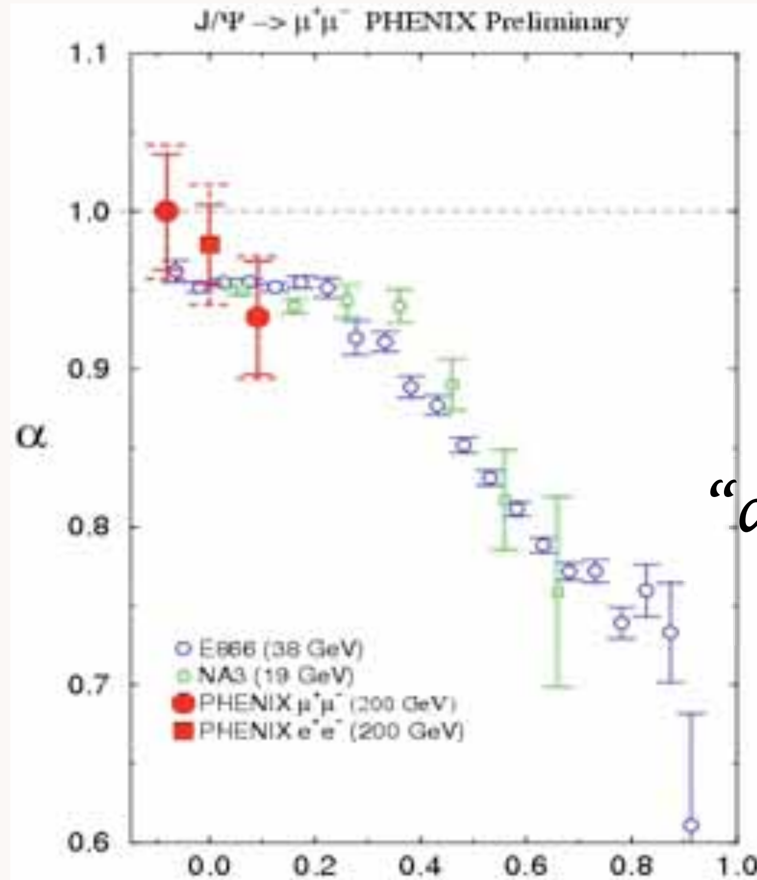
J/ψ nuclear dependence vrs rapidity, x_{Au}, x_F

M.Leitch

PHENIX compared to lower energy measurements



x_2



x_F

Huge "absorption" effect

Klein,Vogt, PRL 91:142301,2003
Kopeliovich, NP A696:669,2001

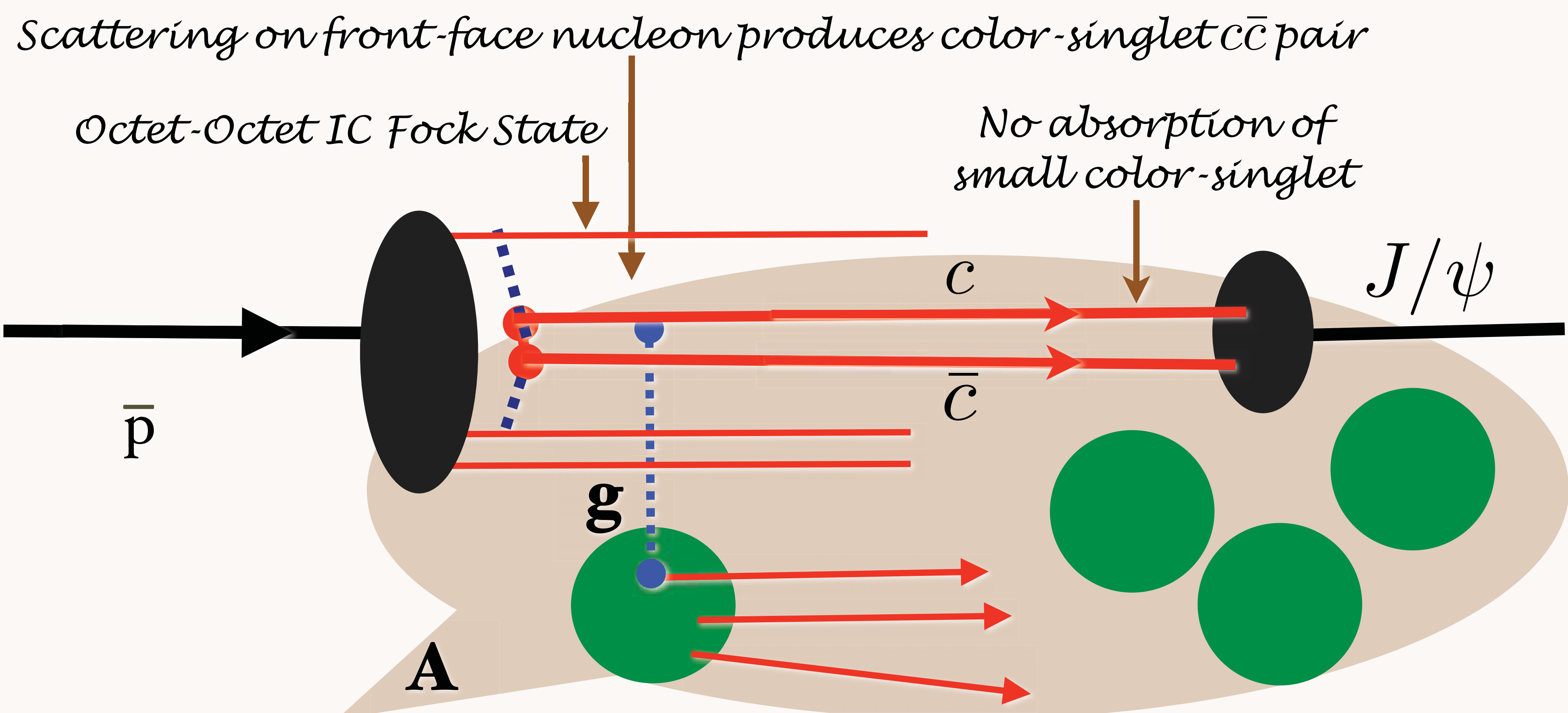
Violates PQCD factorization!

$$\frac{d\sigma}{dx_F}(pA \to J/\psi X)$$

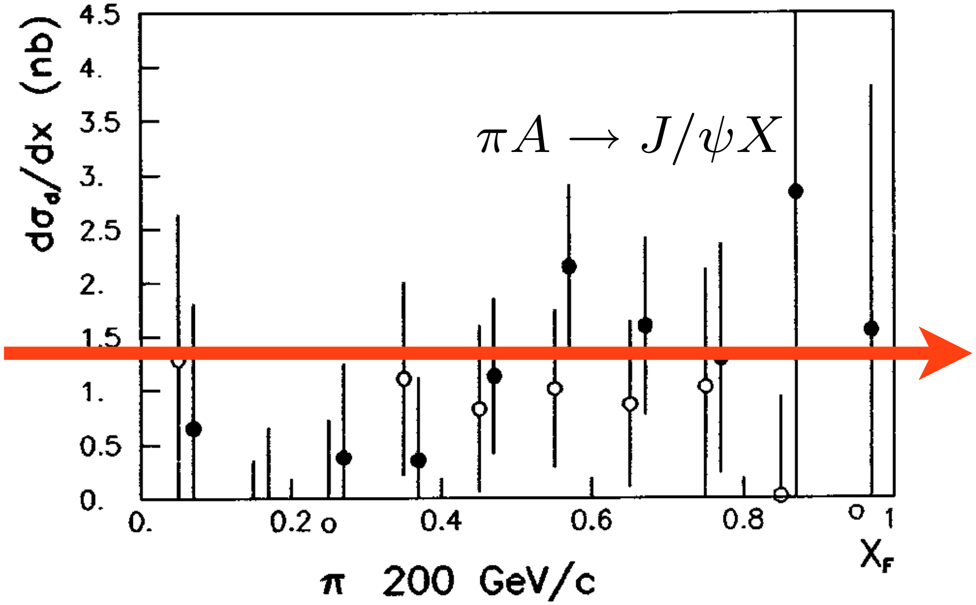
Hoyer, Sukhatme, Vanttinen

Color-Opaque IC Fock state interacts on nuclear front surface

Kopeliovich, Schmidt, Soffer, sjb

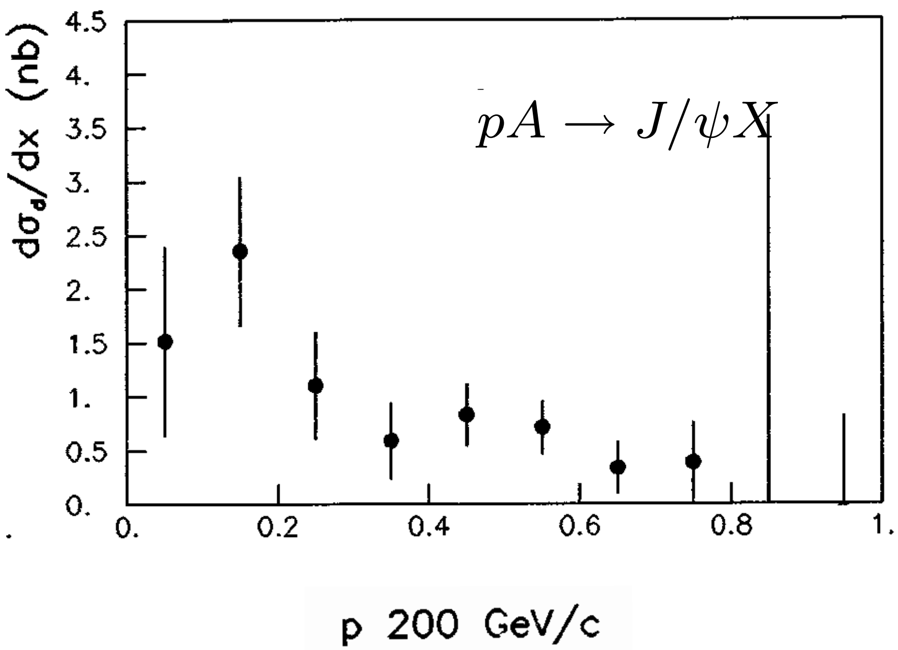


$$\frac{d\sigma}{dx_F}(pA \to J/\psi X) = A^{2/3} \times \frac{d\sigma}{dx_F}(pN \to J/\psi X)$$



$A^{2/3}$ component

J. Badier et al, NA3



$$\frac{d\sigma}{dx_F}(pA \rightarrow J/\psi X) = A^1 \frac{d\sigma_1}{dx_F} + A^{2/3}\frac{d\sigma_{2/3}}{dx_F}$$

Excess beyond conventional PQCD subprocesses

- IC Explains Anomalous $\alpha(x_F)$ not $\alpha(x_2)$ dependence of $pA \to J/\psi X$ (Mueller, Gunion, Tang, SJB)

- Color Octet IC Explains $A^{2/3}$ behavior at high x_F (NA3, Fermilab) (Kopeliovitch, Schmidt, Soffer, SJB)

Color Opaqueness

- IC Explains $J/\psi \to \rho\pi$ puzzle (Karliner, SJB)

- IC leads to new effects in B decay (Gardner, SJB)

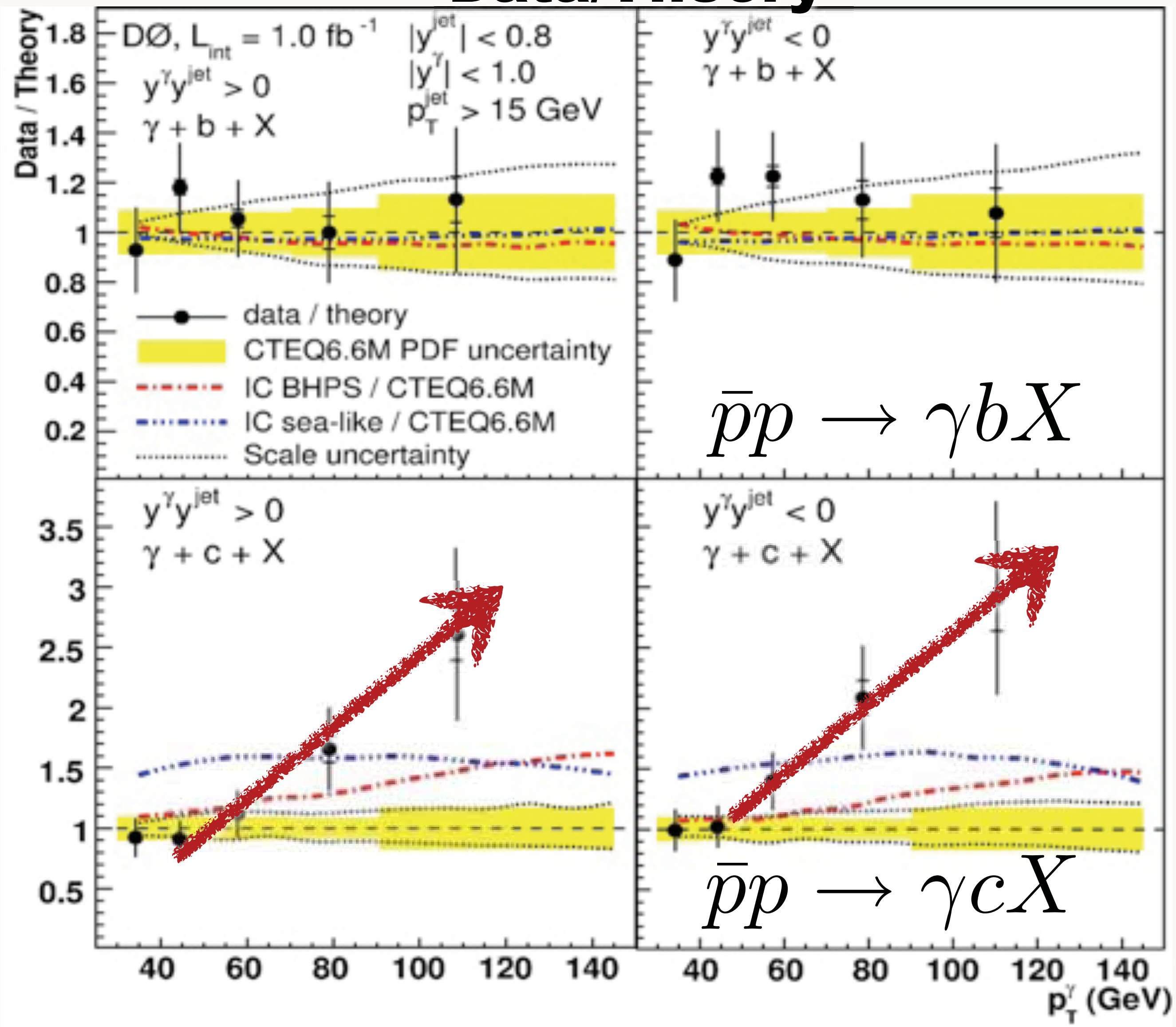
Higgs production at x_F = 0.8 !

Goldhaber, Kopeliovich, Schmidt, Soffer, sjb

PRL 102, 192002 (2009) PHYSICAL REVIEW LETTERS week ending 15 MAY 2009

Measurement of $\gamma + b + X$ and $\gamma + c + X$ Production Cross Sections in $p\bar{p}$ Collisions at $\sqrt{s} = 1.96$ TeV

Data/Theory

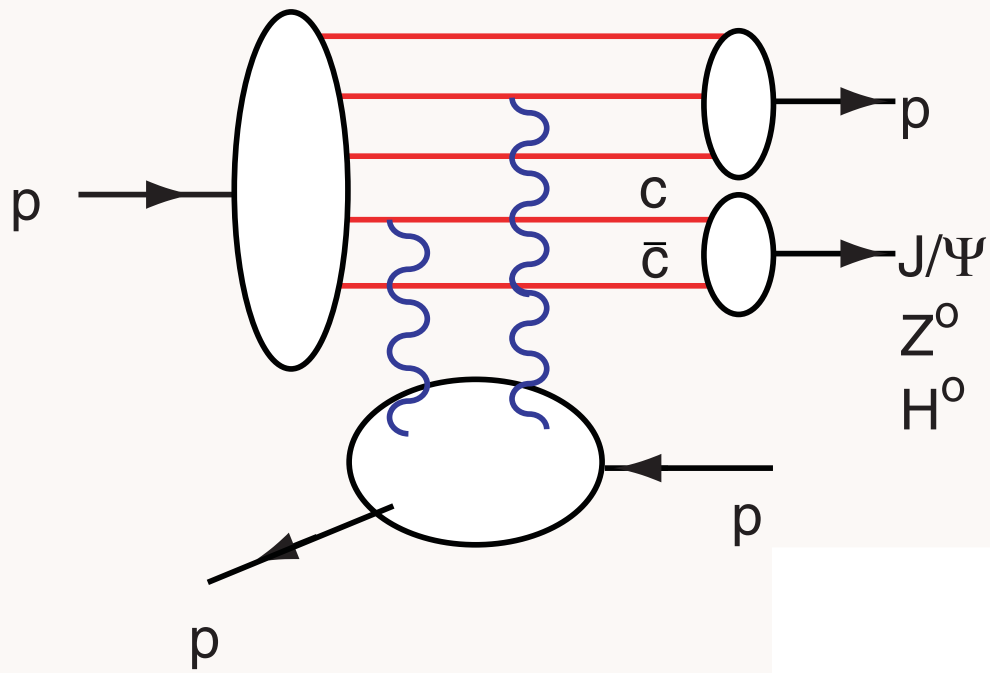


$$\frac{\Delta\sigma(\bar{p}p \to \gamma c X)}{\Delta\sigma(\bar{p}p \to \gamma b X)}$$

Ratio insensitive to gluon PDF, scales

Signal for significant IC at x > 0.1

Intrinsic Charm Mechanism for Exclusive Diffraction Production



$$\mathrm{p\,p} \to J/\psi\ p\ p$$

$$x_{J/\psi} = x_c + x_{\bar{c}}$$

Inclusive and Diffractive High-X_F Higgs Production!

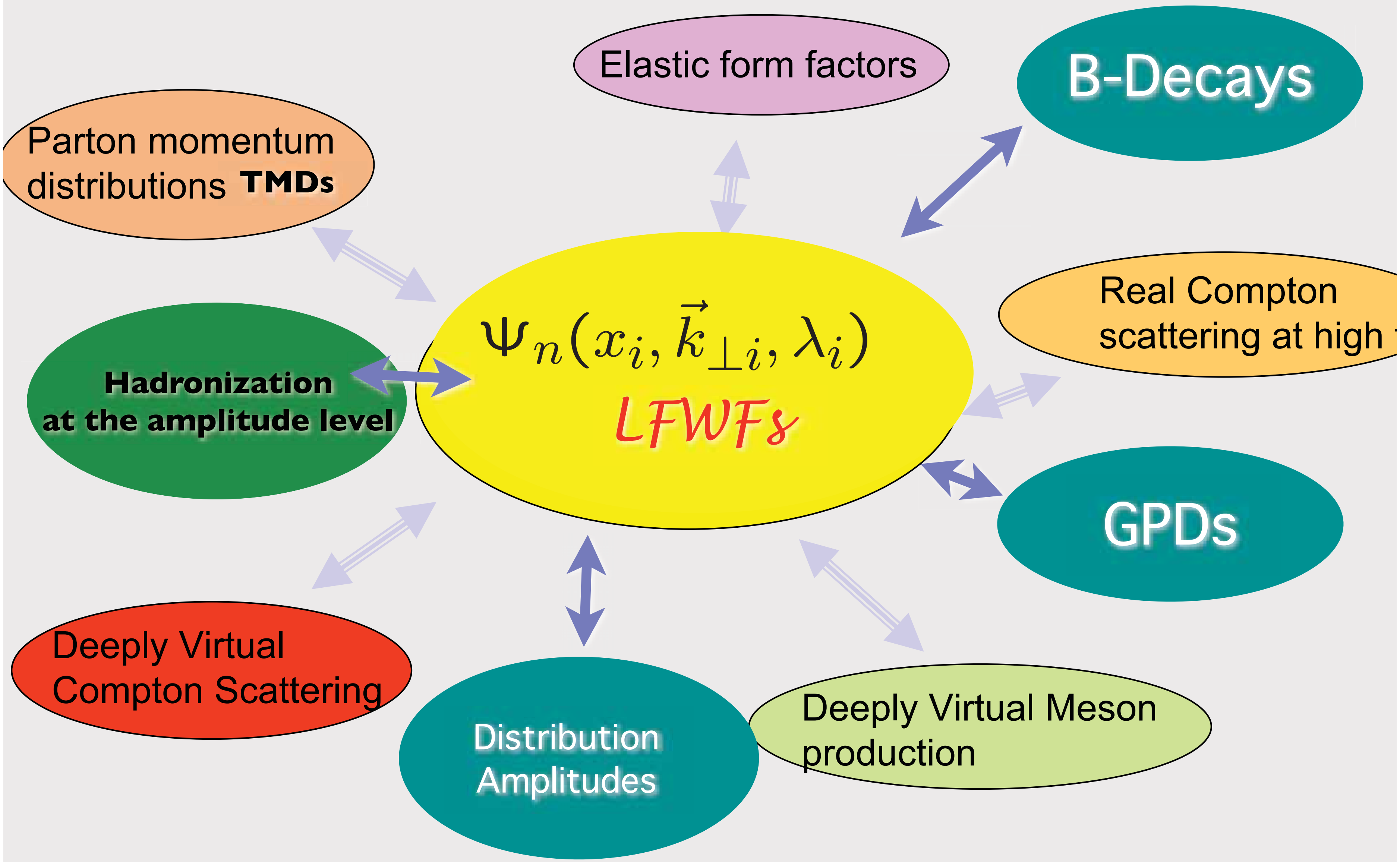
Kopeliovich, Schmidt, Soffer, sjb

Intrinsic $c\bar{c}$ pair formed in color octet 8_C in proton wavefunction   Large Color Dipole

Collision produces color-singlet J/ψ through color exchange

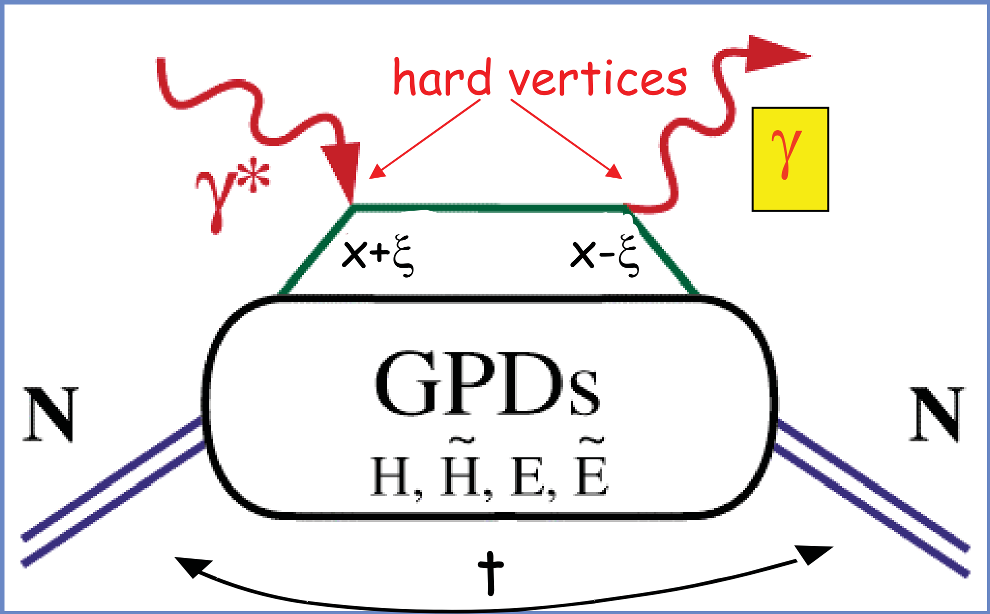
RHIC Experiment

A Unified Description of Hadron Structure



GPDs & Deeply Virtual Exclusive Processes
- New Insight into Nucleon Structure

Deeply Virtual Compton Scattering (DVCS)



x – quark momentum fraction

ξ– longitudinal momentum transfer

$\sqrt{-t}$ – Fourier conjugate to transverse impact parameter

H(x,ξ,t), E(x,ξ,t), . . . "Generalized Parton Distributions"

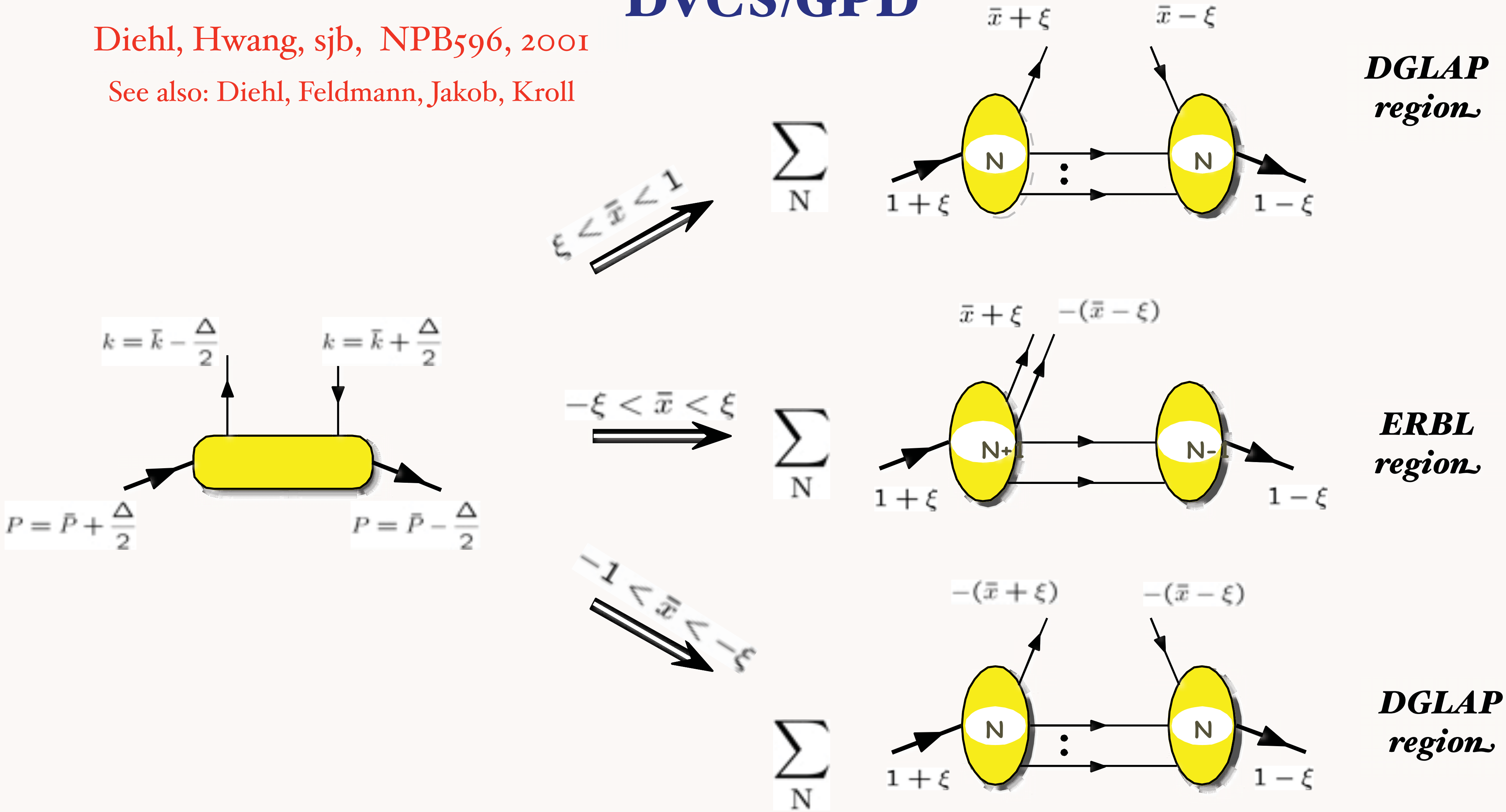
Timelike DVCS: **Mukhurjee,Afanasev, Carlson,sjb**

Light-Front Wave Function Overlap Representation

DVCS/GPD

Diehl, Hwang, sjb, NPB596, 2001

See also: Diehl, Feldmann, Jakob, Kroll



Bakker & Ji
Lorce

Example of LFWF representation of GPDs (n+1 => n-1)

Diehl, Hwang, sjb

$$\frac{1}{\sqrt{1-\zeta}} \frac{\Delta^1 - i\Delta^2}{2M} E_{(n+1\to n-1)}(x,\zeta,t)$$

$$= \left(\sqrt{1-\zeta}\right)^{3-n} \sum_{n,\lambda_i} \int \prod_{i=1}^{n+1} \frac{\mathrm{d}x_i\, \mathrm{d}^2\vec{k}_{\perp i}}{16\pi^3} 16\pi^3 \delta\left(1 - \sum_{j=1}^{n+1} x_j\right) \delta^{(2)}\left(\sum_{j=1}^{n+1} \vec{k}_{\perp j}\right)$$

$$\times 16\pi^3 \delta(x_{n+1} + x_1 - \zeta)\delta^{(2)}\left(\vec{k}_{\perp n+1} + \vec{k}_{\perp 1} - \vec{\Delta}_\perp\right)$$

$$\times \delta(x - x_1)\psi^{\uparrow *}_{(n-1)}\left(x'_i, \vec{k}'_{\perp i}, \lambda_i\right)\psi^{\downarrow}_{(n+1)}\left(x_i, \vec{k}_{\perp i}, \lambda_i\right)\delta_{\lambda_1 - \lambda_{n+1}},$$

where $i = 2, \ldots, n$ label the $n-1$ spectator partons which appear in the final-state hadron wavefunction with

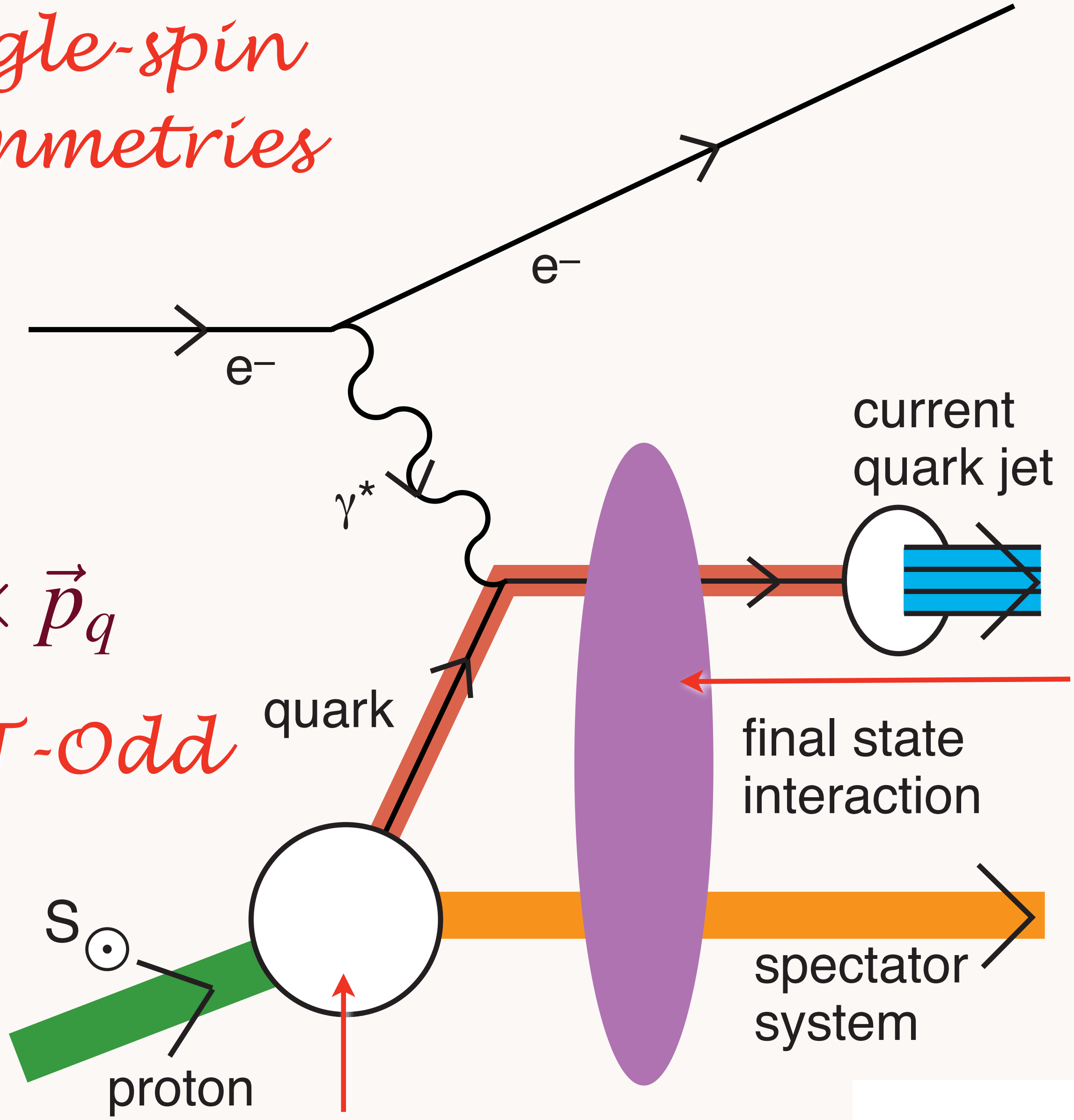
$$x'_i = \frac{x_i}{1-\zeta}, \qquad \vec{k}'_{\perp i} = \vec{k}_{\perp i} + \frac{x_i}{1-\zeta}\vec{\Delta}_\perp.$$

Leading Twist Sivers Effect

Single-spin asymmetries

Hwang, Schmidt, sjb

Collins, **Burkardt**, Ji, Yuan



$$i\ \vec{S}_p \cdot \vec{q} \times \vec{p}_q$$

Pseudo-T-Odd

QCD S- and P-Coulomb Phases --Wilson Line

Light-Front Wavefunction S and P- Waves

Leading-Twist Rescattering Violates pQCD Factorization!

Sign reversal in DY!

Final State Interactions Produce T-Odd (Sivers Effect)

- Bjorken Scaling!
- Arises from Interference of Final-State Coulomb Phases in S and P waves
- Relate to the quark contribution to the target proton anomalous magnetic moment
- Sum of Sivers Functions for all quarks and gluons vanishes. (Zero anomalous gavitomagnetic moment)

$$\vec{S} \cdot \vec{p}_{jet} \times \vec{q}$$

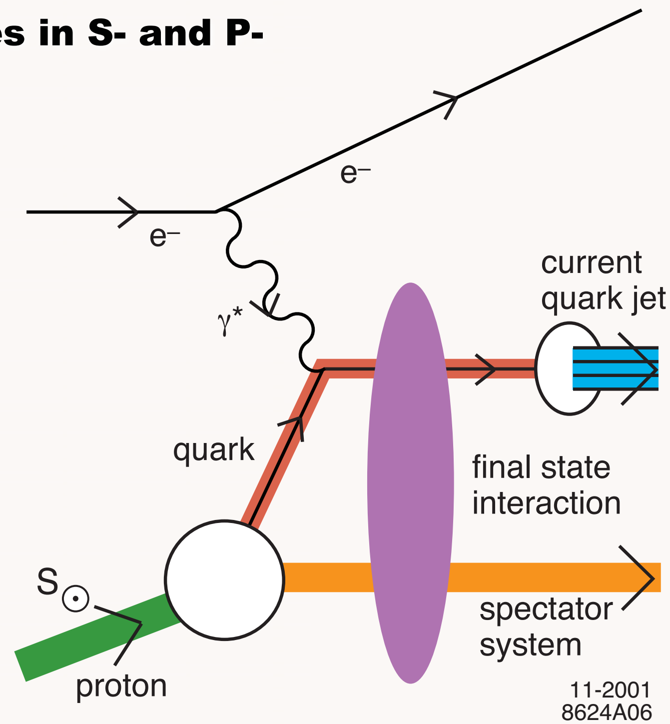
Hwang, Schmidt.
sjb; Burkardt

Final-State Interactions Produce Pseudo T-Odd (Sivers Effect)

Hwang, Schmidt, sjb
Collins

$$\mathbf{i}\ \vec{S} \cdot \vec{p}_{jet} \times \vec{q}$$

- **Leading-Twist Bjorken Scaling!**
- **Requires nonzero orbital angular momentum of quark**
- **Arises from the interference of Final-State QCD Coulomb phases in S- and P-waves;**
- **Wilson line effect -- lc gauge prescription** *Stefanis*
- **Relate to the quark contribution to the target proton anomalous magnetic moment and final-state QCD phases**
- **QCD phase at soft scale!**
- **New window to QCD coupling and running gluon mass in the IR**
- **QED S and P Coulomb phases infinite -- difference of phases finite!**
- **Alternate: Retarded and Advanced Gauge: Augmented LFWFs**



Pasquini, Xiao, Yuan, sjb
Mulders, Boer   Qiu, Sterman

Static	Dynamic
Square of Target LFWFs	Modified by Rescattering: ISI & FSI
No Wilson Line	Contains Wilson Line, Phases
Probability Distributions	No Probabilistic Interpretation
Process-Independent	Process-Dependent - From Collision
T-even Observables	T-Odd (Sivers, Boer-Mulders, etc.)
No Shadowing, Anti-Shadowing	Shadowing, Anti-Shadowing, Saturation
Sum Rules: Momentum and J^z	Sum Rules Not Proven
DGLAP Evolution; mod. at large x	DGLAP Evolution
No Diffractive DIS	Hard Pomeron and Odderon Diffractive DIS

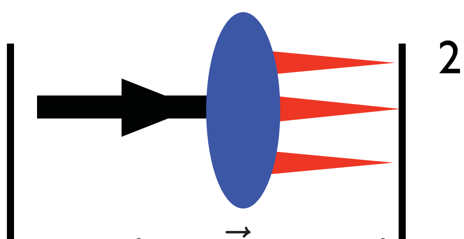
Hwang, Schmidt, sjb,

Mulders, Boer

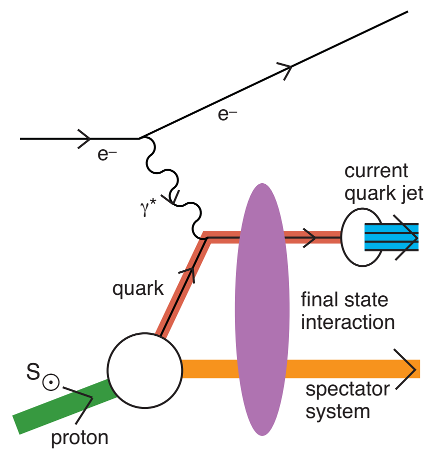
Qiu, Sterman

Collins, Qiu

Pasquini, Xiao, Yuan, sjb



$$\Psi_n(x_i, \vec{k}_{\perp i}, \lambda_i)$$



QCD Lagrangian

gluon dynamics

quark kinetic energy + quark-gluon dynamics

mass term

$$\mathcal{L}_{QCD} = -\frac{1}{4}Tr(G^{\mu\nu}G_{\mu\nu}) + \sum_{f=1}^{n_f} i\bar{\Psi}_f D_\mu \gamma^\mu \Psi_f + \sum_{f=1}^{n_f} m_f \bar{\Psi}_f \Psi_f$$

$$iD^\mu = i\partial^\mu - gA^\mu \qquad [D^\mu, D^\nu] = igG^{\mu\nu}$$

$\lim N_C \to 0$ at fixed $\alpha = C_F \alpha_s, n_\ell = n_F/C_F$

Analytic limit of QCD: Abelian Gauge Theory

QCD → QED

P. Huet, sjb

QED (N_C=0): Underlies Atomic Physics, Molecular Physics, Chemistry, Electromagnetic Interactions ...

QCD: Underlies Hadron Physics, Nuclear Physics, Strong Interactions, Jets

Theoretical Tools

- Feynman diagrams and perturbation theory
- Bethe Salpeter Equation, Dyson-Schwinger Equations
- Lattice Gauge Theory, *Hägler, Lepage*
- Light-Front Methods: Discretized Light-Front Quantization, Transverse Lattice
- AdS/CFT !

LF Quantization

Bjorken, Kogut, Soper, Susskind

LFWFs and Exclusive QCD:

Lepage and SJB, Efremov, Radyushkin

RGE and LF Hamiltonians:

Glazek & Wilson

DLCQ:

Hornbostel, Pauli, & SJB

Pinsky, Hiller

Renormalization of H_{LF}

Hiller, Chabysheva, Pauli, Pinsky, McCartor, Suaya, sjb

Rotation Invariance, Regularization

Karmanov, Mathiot

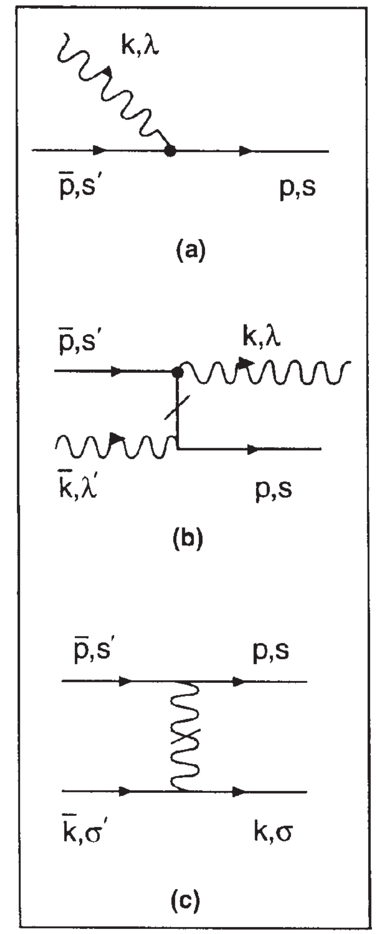
Zero-Modes: Standard Model

Srivastava, sjb

Light-Front formalism links dynamics to spectroscopy

$$L^{QCD} \rightarrow H^{QCD}_{LF}$$

Physical gauge: $A^+ = 0$



Heisenberg Matrix Formulation

$$H^{QCD}_{LF} = \sum_i [\frac{m^2 + k^2_\perp}{x}]_i + H^{int}_{LF}$$

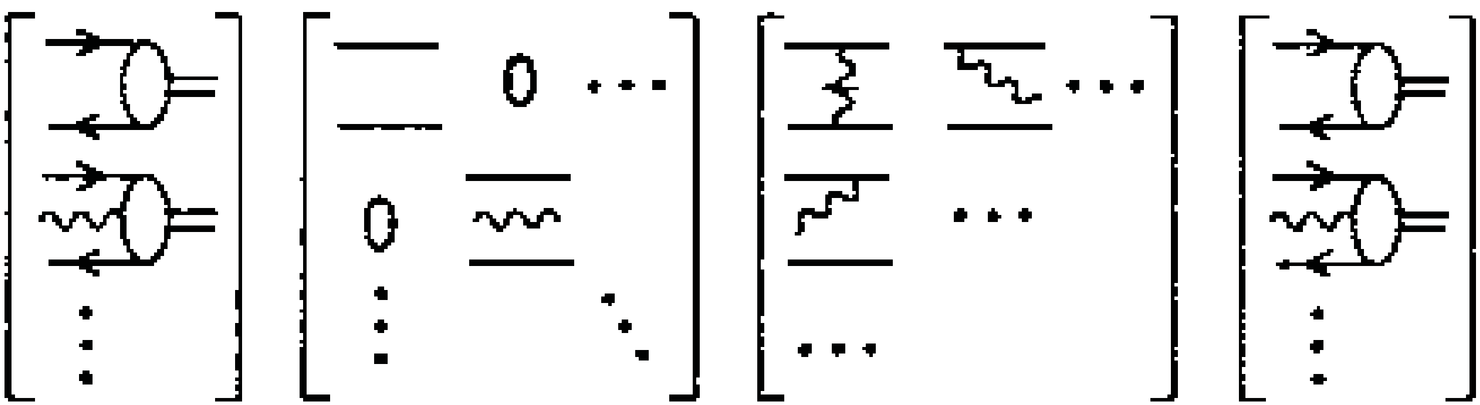
H^{int}_{LF}: Matrix in Fock Space

$$H^{QCD}_{LF} |\Psi_h> = \mathcal{M}^2_h |\Psi_h>$$

Eigenvalues and Eigensolutions give Hadron Spectrum and Light-Front wavefunctions

LIGHT-FRONT SCHRODINGER EQUATION

$$\left(M_\pi^2 - \sum_i \frac{\vec{k}_{\perp i}^{\,2} + m_i^2}{x_i}\right) \begin{bmatrix} \psi_{q\bar{q}/\pi} \\ \psi_{q\bar{q}g/\pi} \\ \vdots \end{bmatrix} = \begin{bmatrix} \langle q\bar{q}|\, V\, |q\bar{q}\rangle & \langle q\bar{q}|\, V\, |q\bar{q}g\rangle & \cdots \\ \langle q\bar{q}g|\, V\, |q\bar{q}\rangle & \langle q\bar{q}g|\, V\, |q\bar{q}g\rangle & \cdots \\ \vdots & \vdots & \ddots \end{bmatrix} \begin{bmatrix} \psi_{q\bar{q}/\pi} \\ \psi_{q\bar{q}g/\pi} \\ \vdots \end{bmatrix}$$



$A^+ = 0$

G.P. Lepage, sjb

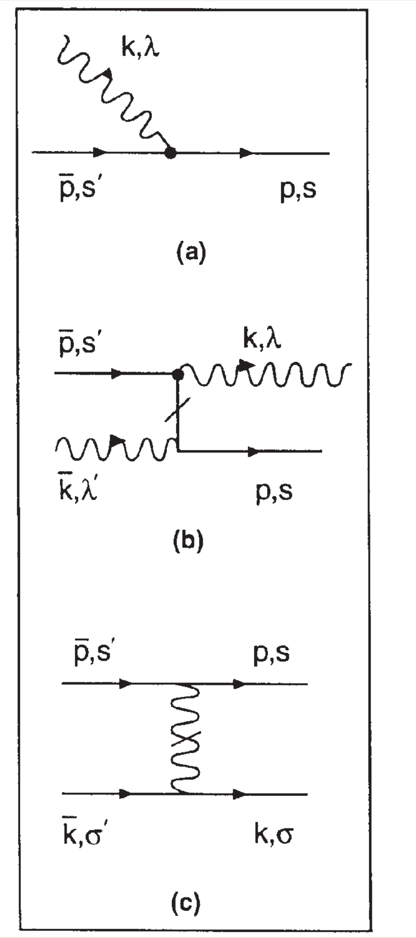
Light-Front QCD

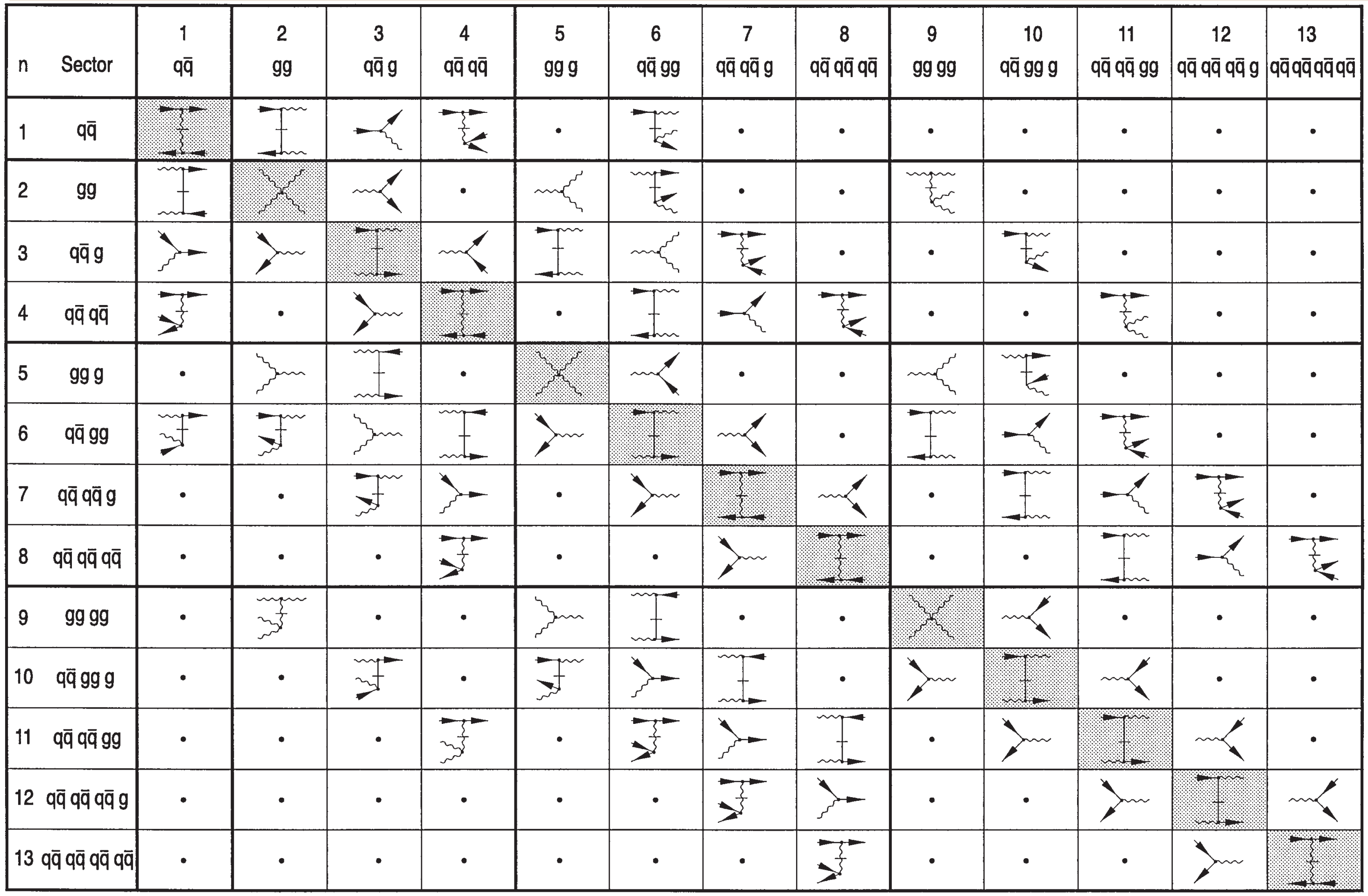
Heisenberg Matrix Formulation

$$H^{QCD}_{LF}|\Psi_h> = \mathcal{M}^2_h|\Psi_h>$$

H.C. Pauli & sjb

Discretized Light-Cone Quantization

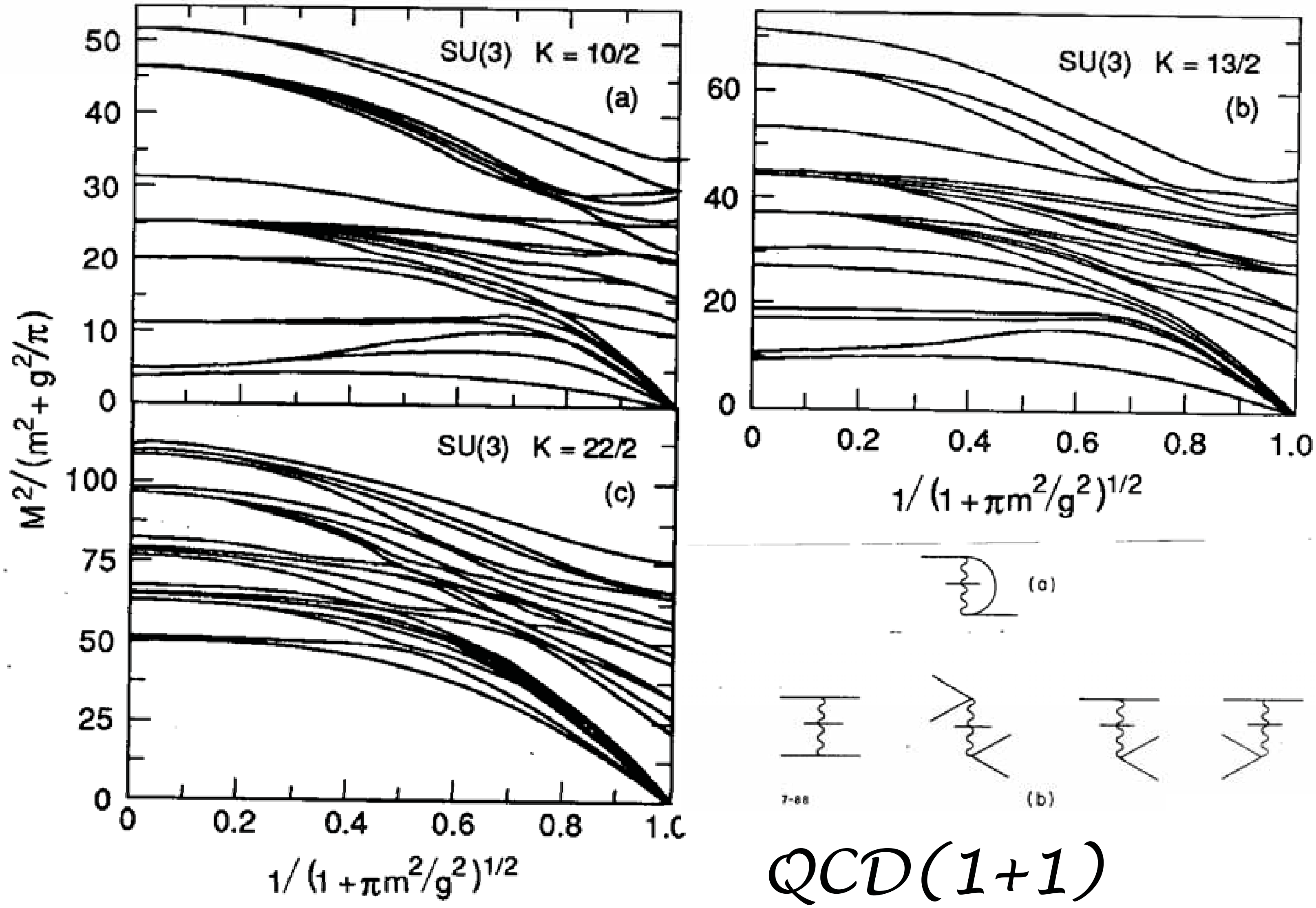




Eigenvalues and Eigensolutions give Hadron Spectrum and Light-Front wavefunctions

DLCQ: Frame-independent, No fermion doubling; Minkowski Space

DLCQ: Periodic BC in x^-. Discrete k^+; frame-independent truncation



Spectra for $N = 3$, baryon number $B = 0, 1$ and 2 as a function of g/m; K fixed.

Light Cone Quantized QCD in (1+1)-Dimensions.
Kent Hornbostel, Stanley J. Brodsky, (SLAC) , Hans Christian Pauli, (Heidelberg, Max Planck Inst.) . SLAC-PUB-4678, **Phys.Rev.D41:3814,1990**.

PHYSICS REPORT

Physics Reports 301 (1998) 299–486

Quantum chromodynamics and other field theories on the light cone

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QUANTUM CHROMODYNAMICS AND OTHER FIELD THEORIES ON THE LIGHT CONE

Goal: an analytic first approximation to QCD

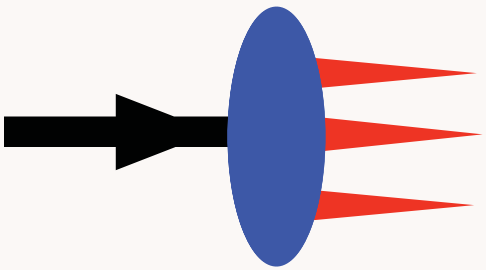
- **As Simple as Schrödinger Theory in Atomic Physics**
- **Relativistic, Frame-Independent, Color-Confining**
- **QCD Coupling at all scales**
- **Hadron Spectroscopy**
- **Light-Front Wavefunctions**
- **Form Factors, Hadronic Observables, Constituent Counting Rules**
- **Insight into QCD Condensates**
- **Systematically improvable**

de Teramond, Deur, Shrock, Roberts, Tandy

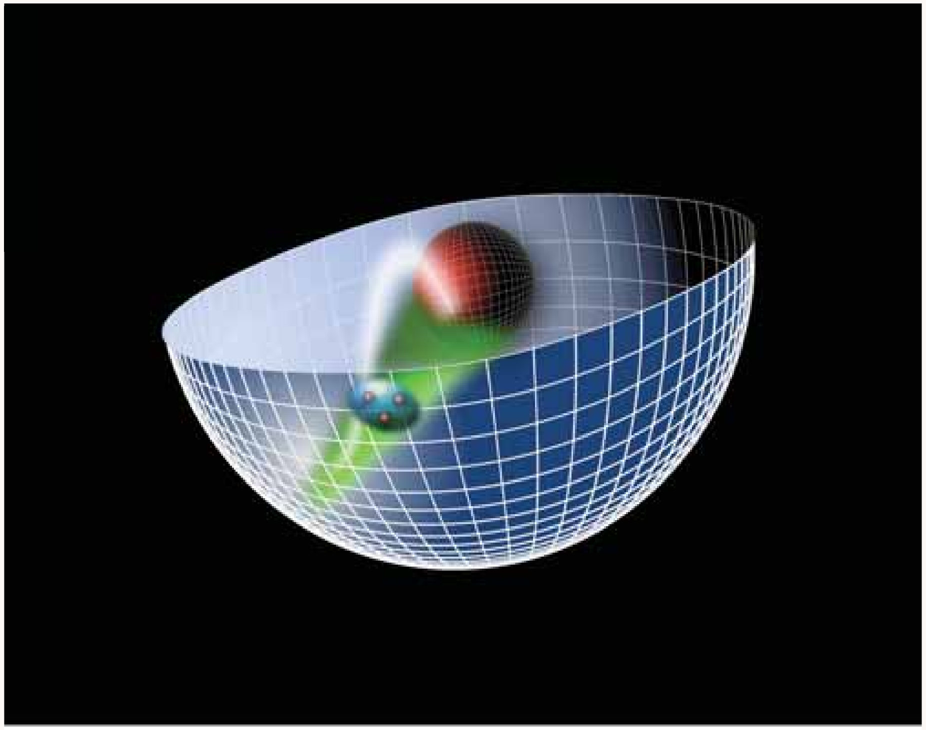
Light-Front Holography and Non-Perturbative QCD

Goal:
Use AdS/QCD duality to construct a first approximation to QCD

Hadron Spectrum
Light-Front Wavefunctions,
Running coupling in IR



$$\Psi_n(x_i, \vec{k}_{\perp i}, \lambda_i)$$



in collaboration with
Guy de Teramond and Alexandre Deur

Central problem for strongly-coupled gauge theories

Light-Front Wavefunctions

Dirac's Front Form: Fixed $\tau = t + z/c$

$$\psi(x, k_\perp)$$

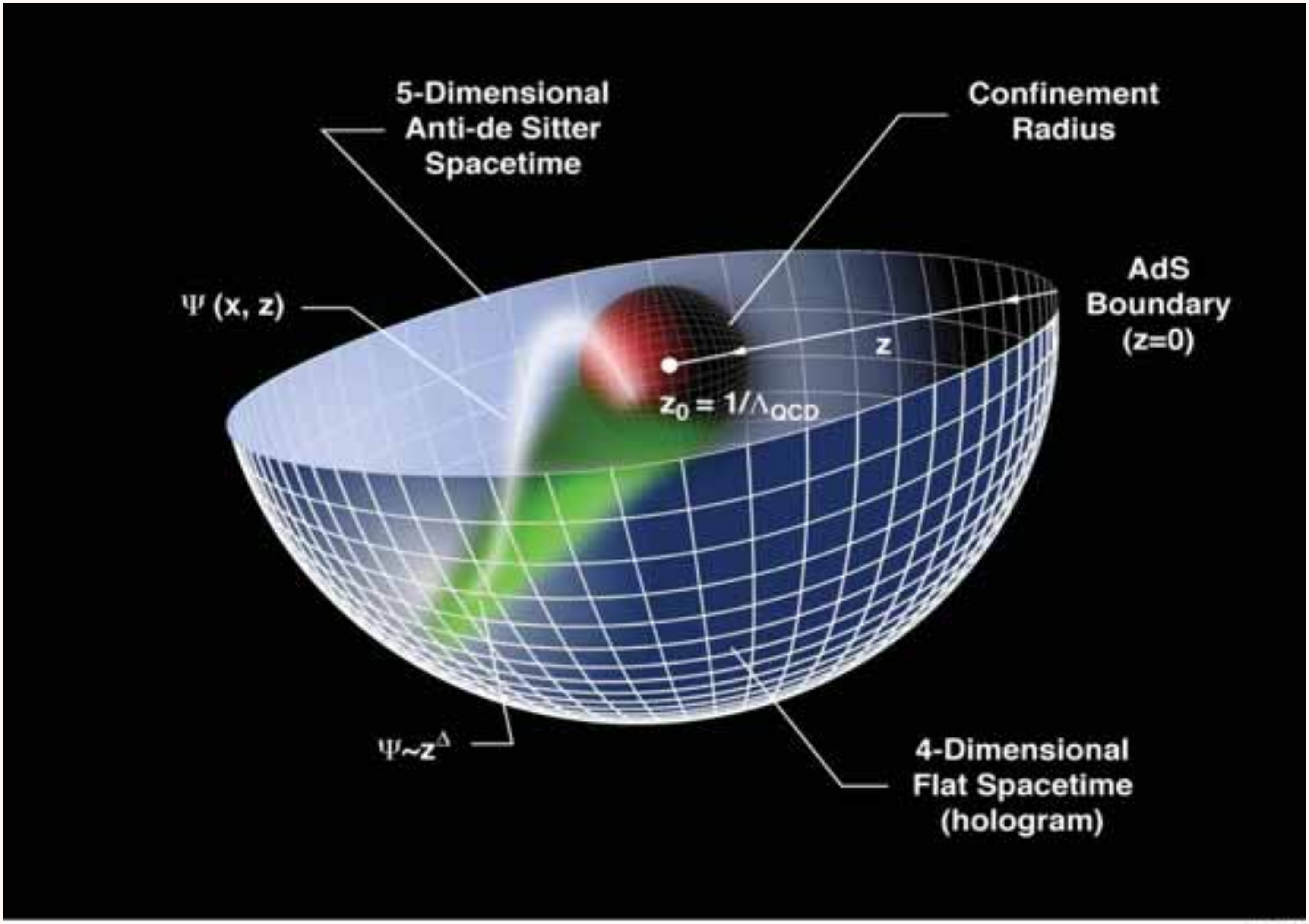
$$x_i = \frac{k_i^+}{P^+}$$

Invariant under boosts. Independent of P^μ

$$H_{LF}^{QCD} |\psi> = M^2 |\psi>$$

Remarkable new insights from AdS/CFT, the duality between conformal field theory and Anti-de Sitter Space

Applications of AdS/CFT to QCD



Changes in physical length scale mapped to evolution in the 5th dimension z

in collaboration with Guy de Teramond

Conformal Theories are invariant under the Poincare and conformal transformations with

$$\mathbf{M}^{\mu\nu}, \mathbf{P}^{\mu}, \mathbf{D}, \mathbf{K}^{\mu},$$

the generators of SO(4,2)

SO(4,2) has a mathematical representation on AdS5

AdS/CFT: **Anti-de Sitter Space / Conformal Field Theory**

Maldacena:

Map AdS_5 X S_5 to conformal N=4 SUSY

- **QCD is not conformal**; however, it has manifestations of a scale-invariant theory: Bjorken scaling, dimensional counting for hard exclusive processes

- **Conformal window:** $\alpha_s(Q^2) \simeq \text{const at small } Q^2$

- **Use mathematical mapping of the conformal group SO(4,2) to AdS5 space**

Deur, Korsch, et al.